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A Survey—Beneficiation of Industrial Minerals, Ores, and Coal by High Intensity Wet Magnetic Separation

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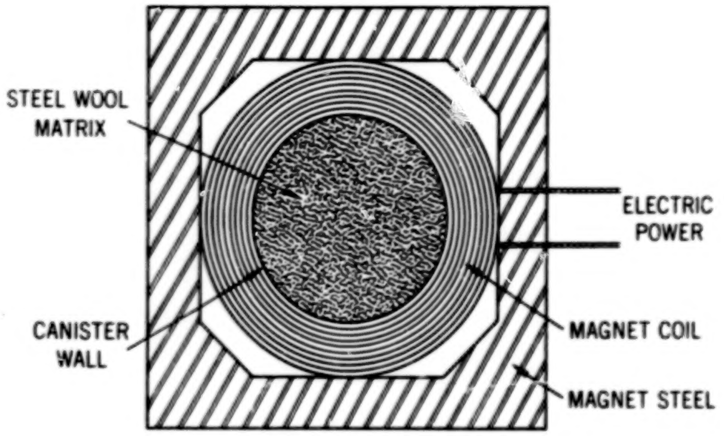
A SURVEY - BENEFICIATION OF INDUSTRIAL MINERALS, COAL, AND METALLIC ORES BY HIGH INTENSITY WET MAGNETIC SEPARATION

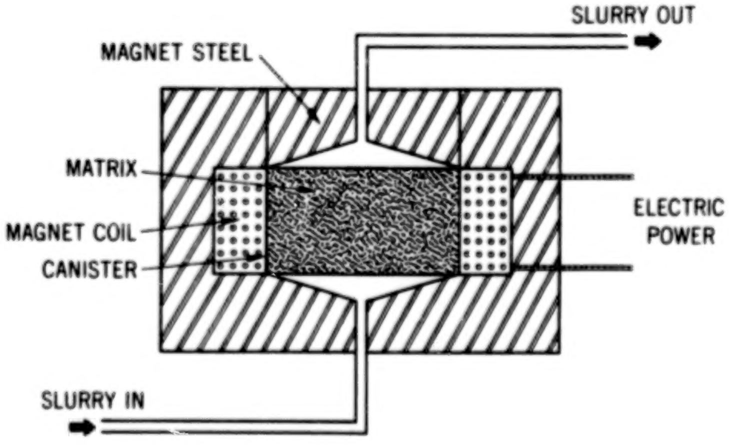
Introduction

Magnetic separation is a well known and widely used method of mineral separation and beneficiation. Conventional magnetic separators are generally restricted to separating strongly magnetic minerals, such as magnetite, iron-rich garnets, etc. High intensity, high gradient magnetic separators capable of attracting weakly paramagnetic particles are now available commercially (Fig. 1). All commercially available high intensity wet magnetic separators have a magnetic circuit design based on the conventional iron yoke surrounded by a coil. The magnetic field is generated by the coil which is water cooled copper wire. Fields up to 20 Kg (kilogauss) are possible when using water-cooled copper coils. This high field opens up a broad spectra of potential applications in minerals and coal beneficiation.

Jones (1) was one of the pioneers in developing a high intensity wet magnetic separator which allowed processing of mineral slurries in fields up to 20 Kg. Frantz (2) developed a canister type of high gradient magnetic filter which was a very important milestone in the development of the modern high gradient magnetic filter which used the canister concept. The magnet is capable of producing a strong adjustable field in the canister volume. The canister volume can be packed with a matrix of steel wool, iron shavings, steel ribbon, Frantz screens, steel shot, or other filamentary ferromagnetic material. Strong magnetic forces produced by the high field gradients at the edges of the filaments are very effective in trapping small particles of even weakly magnetic materials. The



TOP VIEW



SIDE VIEW
SECTION THRU MAGNET

Figure 1 - Diagrammatic representation of high intensity magnetic separator

matrix is chosen to match the size of the feed particles in order to optimize the magnetic field forces. The mineral particles are slurried in water and passed through the canister. The non-magnetic particles in the slurry easily pass through the structure of the matrix if the particle size of both the particles and the matrix are properly matched. The magnetic and/or paramagnetic particles are trapped and held in the canister until the canister is de-energized. These particles are easily washed out when the applied field is reduced to zero.

Oberteuffer (3) indicated that the magnetic force varies as the square of the radius of particles in systems in which the field gradient of the separator matrix material is matched to the size of the particles in the slurry. Thus, the magnetic force falls off significantly in a short distance so that the number of magnetic trapping sites must be very large.

Iannicelli, et al (4), combined the high field strength, the canister concept filled with a magnetic stainless steel wool, and the idea to beneficiate an industrial mineral slurry which in this case was the industrial mineral kaolin. The Georgia and South Carolina sedimentary kaolins contain accessory minerals geothite, limonite, ilmenite, rutile, leucoxene, magnetite, tourmaline, biotite, and muscovite. All of these minerals contain enough iron, either in the mineral structure or intimately associated so that they can be filtered out using a high field strength magnetic separator. This application proved to be very significant and at the moment there are ten or more production magnets installed in kaolin operations in Georgia and three in England and one in West Germany. In addition, three more magnets are on order for installation in the kaolin operations in Georgia and three are on order for European kaolin operations.

Oder and Price (5) described the process and the resultant kaolin products. Their data indicated that kaolin processed through the magnetic separator to remove color bodies was compatible with those processed in the conventional manner. The brightness, particle size, and viscosity compared very favorably with a conventionally processed kaolin by leaching with zinc dithionite. An advantage for the magnetically processed kaolin is that better overall viscosity stability is achieved because of a lower amount of soluble ions which are introduced from the leaching chemicals. Oder and Price (5) were able to produce a kaolin coating clay of No. 1 quality with a 92% brightness using the magnetic process.

Table 1 shows the magnetic susceptibility of several minerals (Strangeway (6)).

TABLE 1 - Magnetic Susceptibilities of Some Common Minerals

Mineral	Magnetic susceptibility, gauss/g.
Biotite	53 = 78 x 10^{-6}
Dolomite	1.8 x 10^{-6}
Garnet	31 - 159 x 10^{-6}
Hausmannite (Mn_3O_4)	54 x 10^{-6}
Hematite	0.4
Ilmenite	19.5 x 10^{-6}
Limestone	3.8 x 10^{-6}
Magnetite	96
Maghemite	90
Millerite	21 x 10^{-6}
Pyrite	0.3 x 10^{-6}
Pyrrhotite	21 x 10^{-6}
Quartz	0.5 x 10^{-6}
Rhodochrosite	100 x 10^{-6}
Rutile	0.07 x 10^{-6}
Siderite	98 x 10^{-6}

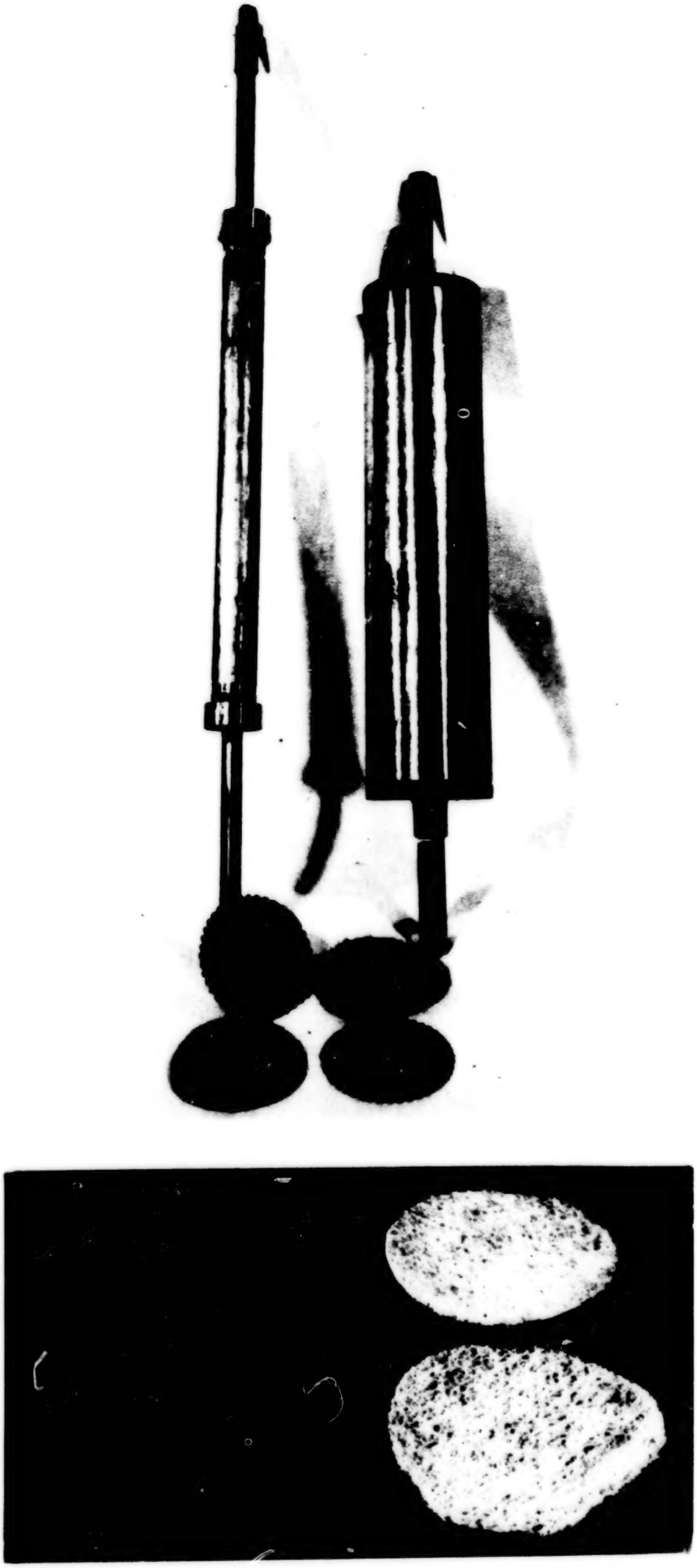


Figure 2 - Canisters and steel wool matrix and Frantz screens

The above table indicates that many minerals associated with industrial minerals have a very wide range of magnetic susceptibilities. For this reason a high field strength with strong gradients is necessary to achieve good beneficiation results. Iannicelli (7) pointed out that the kaolin beneficiation development resulted from the fusing of four major concepts in high extraction magnetic filtration. These concepts are as follows:

1. Discovery of the importance of retention time in mineral separation.
2. Development of very high gradient matrix collectors.
3. High intensity fields in magnetic separators (up to 20 kilogauss).
4. Modern design of large high field magnets.

Prior to the kaolin development it is difficult to find instances where the actual magnetic separation process was controlled to act on the particles in slurry for more than a few seconds. Use of longer retention time permits finely divided particles to migrate and be captured by a magnetized collection surface. The use of longer retention times dictates reduced velocities of slurry relative to magnetic collecting elements so that the resulting reduction in drag forces permits better capture and retention of weakly magnetic particles.

The canister (Fig. 2) in this study was filled with a special stainless steel wool or a matrix of Frantz screen made of thin sharp ribbons of 430 magnetic stainless steel. The diameter of the canister ranges from 1 inch in diameter for laboratory studies, 5 inches in diameter for the pilot plant model and up to 84 inches in diameter for the largest available commercial unit. Fabrication of equipment larger than 84 inches is feasible. A larger unit for on site assembly is being built at the present time for delivery in 1980.

The high intensity magnetic separator has a maximum field of 10 to 20 thousand gauss, about ten times greater than the field strength of ordinary hand magnets.

The maximum value of 20,000 gauss represents the saturation magnetization of ordinary soft iron, which is often used in conjunction with electric-current-carrying coils to give a high magnetic field without excessive current consumption, much higher continuous fields can be obtained in water-cooled solenoids up to 250,000 gauss. The development of super-conducting solenoids makes available continuous fields up to 80,000 gauss with minimal power consumption. Although it is not commercially available at present, many expect a superconducting magnetic separator to be developed.

A high magnetic field alone is not sufficient for separating paramagnetic minerals, but in addition, there must be a high field gradient. In high intensity magnetic separators, it is customary to use in the canister or separation zone a matrix of shaped iron pieces that produce high field gradients and act as collection sites for the paramagnetic particles. The matrix should be chosen to best fit the character of the material to be separated. The characteristics that should be considered in selecting a matrix include the following:

1. Maximum magnetic field gradient.
2. Volume average magnetic field gradient.
3. Collection surface area per unit volume of collection zone.
4. Capability of cleaning the matrix of ferromagnetic particles with little or no separator shutdown time.
5. Permeability of matrix to fluid flow.
6. Magnetic permeability of matrix.

Two parameters which characterize any matrix of a given geometry are its size and porosity, and the ratio of void volume to total volume. The iron used to form the matrix should be as magnetically "soft" as possible which means that it should retain a minimum of magnetization when removed from the external magnetic field. If the matrix retains a significant amount of magnetization, it becomes nearly impossible to remove trapped ferromagnetic particles without disassembling the matrix.

Description of HEMF Equipment

The magnetic separator used in this study was a pilot plant model manufactured by Pacific Electric Motor Co. of Oakland, California. The unit is designated a 5 inch pilot plant magnetic separator. The HEMF equipment consists of a filter canister packed with a matrix of compressed magnetic stainless steel wool. The matrix material can be easily changed. The canister is surrounded by hollow conductor copper coils which energize the entire canister to a field of 20 kilogauss. Coils are in turn surrounded by a box-like enclosure of steel plate which completes the magnetic circuit. The unit operates at power levels of 200 kilowatts.

The specifications of the P.E.M. 5 inch Magnetic Filter System are as follows:

Magnetic Filter

Magnet field intensity without filter bed - 20 kilogauss @ 200 KW D.C. -800A and 250 volts

Filter bed diameter - 5 inches

Filter bed depth - 20 inches

Filter bed volume - 390 in^3

Filter bed stainless steel canister designed for 100 psi working pressure and 300 psi test pressure

Magnet closed loop water flow - 40 gpm

200 KW D.C. Power Supply

3 phase A.C. power input - 225 KVA @ 575, 480, or 240 volts (only one of above voltages furnished

D.C. current continuously variable from 0 - 800 amps.

Water to water heat exchanger

Closed loop side complete with 5 hp pump, hoses, demineralizer, temperature and pressure gauges, and flow eye (pump motor 3 phase 230/460V).

Open loop side requires 80 gmp for operation at maximum power.

The equipment will shut down under any of the following conditions:

a. Power supply diode and S.C.R. heat sink over temperatures or heat sink insufficient water flow.

b. Magnet closed-loop water over-temperature, or insufficient closed loop water flow.

Magnet and power supply approximate dimensions

120" x 24" x 50"

Weight - 6500 lbs.

Water to water heat exchanger dimensions

60" x 24" x 30"

Weight - 500 lbs.

Minerals and Coal Beneficiation

Industrial Minerals. As previously mentioned high gradient magnetic separators are used successfully in the kaolin industry (8), (9). Mills (8) stated that "Magnetic separation is metallurgically comparable to flotation for the production of high brightness (89+) clays, and is not only a more economical approach, but also one that is considerably easier to control." Iannicelli (personal communication) reports that operating costs for general purpose kaolin beneficiation is \$1.62/ton (66 tons/hour, 30 second retention) and \$4.10/ton for specialty kaolin (15 tons/hour, 120 second retention). The high intensity magnetic separation process for kaolin beneficiation has increased the useable reserves in Georgia substantially and also permitted making high brightness coating clays at a reduced cost with better rheological properties.

Non-metallic mineral production in the United States in 1978 had a total value of 12.8 billion dollars. These minerals are used in almost every process industry, as building materials, and many others (10). The standard of life in the United States is in large part due to the availability and abundance of these relatively inexpensive industrial minerals. Minerals are not renewable and are a depletable asset. Therefore, we must conserve our natural resources and find ways to beneficiate submarginal deposits into useable products.

In the field of industrial minerals iron (and in many instances titanium) is an element which is deleterious to the end use. In industrial minerals that are utilized as white pigments, fillers, and extenders, the iron and titanium minerals are colorants that reduce the whiteness and brightness values. In ceramic applications iron containing minerals are detrimental because they affect the fired color and reduce the refractoriness. The presence of iron in industrial minerals that are used in making glass lowers the clarity of the glass. Thus it can be seen that the removal or reduction in iron and titanium is important. The successful application of high intensity magnetic separation to beneficiate kaolin led to this project at Indiana University to survey the effect of magnetic separation as a beneficiation process on other industrial minerals, coal, and selected metallic ores.

Coal. The current energy program in the United States to develop our domestic energy resources necessarily means that we must utilize our coal resources. Coal is the largest fossil fuel resource in the United States with approximately 180 billion tons of currently recoverable reserves (11), (12). The major difficulty with coal utilization lies with the pollution problem particularly with sulfur oxide emissions. Available methods for controlling sulfur oxide emissions from stationary combustion sources fall into three categories (13).

1. The physical removal (coal cleaning) of pyritic sulfur prior to combustion.
2. The removal of sulfur oxides from the combustion flue gas.
3. Conversion of coal to a clean fuel by such processes as gasification, liquifaction, and chemical extraction.

The first method, physical removal of pyritic sulfur, is the most developed method technologically and is potentially lowest in cost. The amount of sulfur reduction is limited, however, to the sulfur that is present in inorganic minerals, the most common of which is the mineral pyrite (FeS_2). Sulfur in coal occurs in three forms: pyritic, sulfate, and organic.

Pyritic sulfur accounts for 40 to as much as 80 percent of the total sulfur content of most coals (14). In the bituminous coals from Illinois, for example, the mean total sulfur content in 474 analyses was 3.57 percent and the mean value of pyritic sulfur was 2.06 percent (15).

Pyrite (FeS_2) occurs in coal as discrete particles, some large, but often as microscopic to submicroscopic size.

1. Veins usually thick and filmlike along vertical joints
2. Lenses that are extremely variable in shape and size
3. Nodules or balls
4. Disseminated crystals and irregular aggregates

Microscopic pyrite occurs in coal as:

1. Small globules and blebs
2. Fine veinlets
3. Dendrites
4. Small euhedral crystals
5. Cell fillings
6. Replacement of plant material

The coarse macroscopic pyrite is relatively easy to separate because it is much heavier than coal. The microscopic fine pyrite, however, is difficult to remove because it is usually disseminated throughout the coal. Pyrite is a heavy mineral with a specific gravity of about 5.0 compared to coal which has a specific gravity of the order of 1.5. Therefore, the coarse pyrite can be removed by washing or using a preselected heavy liquid with a specific gravity of 1.7 or above. Gravity separation of fine pyrite and fine coal is difficult and a relatively efficient process is needed to beneficiate fine coal and remove fine pyrite. Presently used methods of physical separation of pyrite normally remove up to 50 percent of the pyrite which in most of the Eastern U.S. coals is not enough.

The earliest work concerning the reduction of sulfur in coal by magnetic separation was described in a German patent by Siddiqui in 1957 (16). Yurovsky and Remesnikov (17) published a paper reporting that coal pulverized finer than

16 mesh size subjected to a thermal steam-air treatment reportedly made the pyrite more magnetic, which enhanced beneficiation when processed in a specially built magnetic separator. Reductions of 85, 74.9, and 70 percent of the pyritic sulfur were reported. Perry (18) reported that fine pyrite (64 to 100 mesh) treated in a steam-air atmosphere at temperatures of 570° to 750°F for varying times up to 10 minutes resulted in increased quantity of pyrite becoming amenable to magnetic separation with increasing intensity of treatment. Kester (19) demonstrated that sulfur could be reduced to a greater extent by making a high intensity magnetic separation directly on the raw untreated coal without employing the thermal pretreatment step. Thus, by pulverizing the coal to a typical power plant size and by magnetically separating the coarse 48 to 200 mesh size fraction, significant sulfur reduction was achieved.

Coal is diamagnetic (20) and pyrite is paramagnetic. Thus, if the coal is crushed and pulverized fine enough to liberate the pyrite then separation by magnetic means is possible. The separation of pyrite from coal involves a variety of problems according to Ergun and Bean (21). The first major problem is that the pyrite particles must be adequately liberated from coal particles. A second problem is that pyrite is more magnetic than coal but the susceptibility is low and no measurements are available which would indicate the amount of force necessary for the separation. Third, it has been stated that pyrite can be converted into ferromagnetic compounds with special treatments but no rates of formation are given. They concluded that there is a need for far more elaborate and conclusive studies.

A second part of the study by Ergun and Bean (21) was to determine the size distribution of pyrite particles in coals. They found a range from submicron to several millimeters. In addition they measured the magnetic susceptibilities of some U.S. coals and determined that they are indeed diamagnetic. They also measured the magnetic susceptibilities of some compounds of iron which are shown in the following table.

TABLE 2 - Magnetic susceptibilities (field strength 6000 gauss) of iron, pyrite and other compounds of iron into which pyrite may be converted (after Ergun and Bean (21)).

Compound	Magnetic Susceptibility, X, in 10G cgs Units	
	Per Gram Compound	Per Gram Iron
Iron, Fe	34,000	34,000
Cementite, Fe_3C	20,600	22,100
Magnetite, Fe_3O_4	15,600	21,600
Gamma-Hematite, γ -Fe_2O_3	15,600	22,300
Monoclinic Pyrrhotite, $FeS_{1.4}$	2,800	4,600
Melanterite, $FeSO_4$ 7 H_2O	41.5	206
Alpha-Hematite, α -Fe_2O_3	20.6	29.4
Pyrite, FeS_2	0.30	0.64

Recently Kindig and Turner (22) reported on a new process for removing pyritic sulfur and ash from coal. Feed coal is contacted with iron carbonyl vapors, $Fe(Co)_5$, at 190°F which puts a thin skin of magnetic material on the pyrite and ash, but does not affect the coal. Thus, low intensity magnetic separators yield a nonmagnetic coal, low in sulfur and ash, and a magnetic refuse, high in sulfur and ash. The raw coal is first crushed to liberate impurities. The crushed coal is heated and conditioned, then treated with iron carbonyl. Coal from the Lower Freeport seam was tested and ash was reduced from 27% to 9% and pyritic sulfur from 2.1% to 0.3%. The yield of clean coal was 73%. These results were obtained with 4 lb./ton (0.2%) of iron carbonyl. When 3.1% (62 lb./ton) iron carbonyl was tried ash was reduced from 27% to 4.8% and pyritic sulfur from 2.12% to 0.18%. The yield of clean coal was 64%. A major disadvantage of this process is that iron carbonyl is a highly toxic material.

In summary, the earlier work used either low-intensity or low-gradient magnetic separators as the new generation high gradient magnetic separators were not available until after 1970. Therefore, a pilot scale study of pyritic sulfur and ash removal from coal using a high intensity, high gradient magnetic separator is in order.

Metallic ore minerals. Magnetic separation is an important process that has been used in mineral dressing for many years. Most metallic ores are crushed and the values are concentrated using flotation, gravity settling, electrostatic separation, or other special processes. Wyman, Stone, and Hartman (23) reported on test work conducted on several metallic ores using a Jones wet magnetic mineral separator. However no work has been reported using new high intensity, high gradient magnetic separators on metallic ores. Because many of the oxides and sulfide ore minerals are magnetic or paramagnetic high intensity, high gradient magnetic separation has a good chance of concentrating the valuable ore minerals.

Experimental Procedures

Two canister sizes were used in the magnetic separator dependent upon the quantity of sample available to run. The standard 5 inch (12.7 cm) diameter canister was used for large sample runs and a 1 inch (2.52 cm) diameter canister for small sample sizes. After experimenting with matrices of stainless steel wool pads, stainless steel wool roving, steel shavings, steel ribbons, and Frantz screens, the two matrices that were used in the experiment were stainless steel wool pads packed into the canister so that 6 percent of volume was occupied, and Frantz screens. Medium and fine particle size materials (44 micrometers or less) were run through the 6 percent volume stainless steel wool and coarse materials (sand size) were run through the Frantz screens.

Samples were prepared in slurry form by mixing the sample in water dispersed with the aid of sodium hexametaphosphate using a Waring blender or a Bodine mixer. The sample size ranged from 500 gms to 2000 gms and the percent solids from 10 to 30 percent. A masterplex peristaltic pump was used to force the slurry through the canister at a controlled rate so that the retention time in the magnetic field could be controlled. Pumping rates were used so that the mineral particles were retained in the magnetic field for 30 seconds, one minute and two minutes. A control sample and the magnetic and non-magnetic portion of the 30 second, one minute, and two minute retention times were collected for analysis.

The industrial minerals samples were analyzed for iron and/or titanium and in some instances for potassium. On certain industrial minerals that are used for fillers, pigments, or extenders, brightness values were determined using a standard brightness measuring technique prescribed by the Technical Association of the Pulp and Paper Industry (24).

The coal samples were pulverized to minus 100 mesh, minus 200 mesh, and minus 325 mesh. The control, magnetic, and non-magnetic portions of the samples were analyzed for total sulfur and inorganic sulfur; the organic sulfur was determined by difference.

The metallic ore samples were run as received which was the particle size used for the flotation process or were rod milled to a size less than 44 microns (325 mesh). The control and magnetic and non-magnetic portions of the samples were analyzed for the appropriate metallic values.

Most samples were run at 20 kilogauss field intensity except where noted. Standard analytical techniques were used for all chemical analyses and duplicate and some triplicate samples were run.

HIMS of Industrial Minerals

The 43 industrial mineral samples and their location are listed in Table 3. As mentioned earlier, industrial minerals are essential to maintain our industrial growth. With continuing population growth and industrial expansion, the production and reserves of industrial minerals must be increased in order to sustain our quality of life. Beneficiation of marginal and submarginal ores is one way to increase reserves and improve the quality of many production grades of certain industrial minerals (10). It has been suggested that the successful application of HIMS in the kaolin industry in Georgia (5, 8, 9) has doubled the kaolin reserves.

The results obtained in testing the many industrial minerals were varied with some being positive and some negative. The data collected on these minerals are included and discussed. Some excellent results on certain minerals resulted in more detailed evaluations which are presented. For some minerals the data are presented in tabular form whereas for others the data are on figures. Each industrial mineral tested is discussed separately in alphabetical order.

TABLE 3 - Sample location of industrial minerals.

	INDUSTRIAL MINERAL	SAMPLE LOCATION
1.	Asbestos	Coalinga, California
2.	Attapulgite	Attapulgus, Georgia
3.	Ball Clay	Paris, Tennessee
4.	Ball Clay	Mayfield, Kentucky
5.	Barite	Washington County, Missouri
6.	Barite	Cartersville, Georgia
7.	Barite	Battle Mountain, Nevada
8.	Bauxite	Bauxite, Arkansas
9.	Bauxite	Paranam, Surinam
10.	Bauxite	Clarendon, Jamaica
11.	Bauxite	Weipa, Queensland, Australia
12.	Bentonite	Gonzales, Texas
13.	Bentonite	Casper, Wyoming
14.	Bentonite	Amargosa Valley, Nevada
15.	Calcite	Llano, Texas
16.	Calcite	Baltimore, Maryland
17.	Diatomaceous Earth	Lompoc, California
18.	Diatomaceous Earth	Lovelock, Nevada
19.	Feldspar	Bryson City, North Carolina
20.	Fluospar	Cave-in-Rock, Illinois
21.	Glass Sand	Ottawa, Illinois
22.	Glass Sand	Berkeley Springs, West Virginia
23.	Graphite	Burnet County, Texas
24.	Hectorite	Hector, California
25.	Hectorite	Amargosa Valley, California
26.	Kaolin	Kosse, Texas
27.	Kyanite	Washington, Georgia
28.	Magnesite	Gabbs, Nevada
29.	Mica	Randolph County, Alabama
30.	Nepheline Syenite	Blue Mountain, Ontario, Canada
31.	Novaculite	Malvern, Arkansas
32.	Olivine	Asheville, North Carolina
33.	Pyrophyllite	Robbins, North Carolina
34.	Phosphate Slimes	Lakeland, Florida
35.	Saponite	Amargosa Valley, Nevada
36.	Sepiolite	Amargosa Valley, Nevada
37.	Spodumene	Kings Mountain, North Carolina
38.	Talc	Yellowstone, Montana
39.	Talc	Willow Creek, Montana
40.	Talc	Beaverhead, Montana
41.	Tripoli	Cairo, Illinois
42.	Volcanic Ash	Gonzales County, Texas
43.	Wollastonite	Willsboro, New York

ASBESTOS

Asbestos is a commercial term applied to several minerals utilized for their fibrous qualities. Chrysotile, a variety of serpentine, is a hydrous magnesium silicate and is the most common of the asbestos minerals.

Sample location - Coalinga, California

Test conditions - Particle size - 100% through a 200 mesh sieve

Canister matrix - Steel wool

Retention time - 30 seconds, 1 minute, 2 minutes

Field strength - 20 kilogauss

Percent solids - 20 - Dispersed with sodium hexametaphosphate

TABLE 4 - Fe and TiO_2 in asbestos HIMS fractions

Sample	Percent Fe	Percent TiO_2
Control	4.36	0.13
30 second non-magnetic	2.58	0.09
1 minute non-magnetic	2.40	0.08
2 minute non-magnetic	2.30	0.08

Discussion - Chrysotile, an asbestos mineral, is used primarily as a reinforcing agent or as insulation. It is also used as a filler in paper and as a thickener in paints so that color is important. Iron bearing minerals such as magnetite, goethite, and ilmenite are the chief colorants for the Coalinga chrysotile so a reduction in iron content improves the color and removes the harder iron mineral particles which are abrasive. The high intensity magnetic separation removes a considerable portion of the iron with only a 30 second retention time in the field. Therefore, this type of beneficiation shows promise as a method to substantially reduce the iron content of the Coalinga asbestos.

ATTAPULGITE

Attapulgite is a hydrated magnesium silicate clay mineral that is used primarily as an absorbent. This type of clay is generally called "fuller's earth."

Sample location - Attapulgus, Georgia
Test conditions - Particle size - minus 325 mesh
Canister matrix - Steel wool
Retention time - 30 seconds, 1 minute, 2 minutes
Field strength - 20 kilogauss
Percent solids - 20 - Dispersed with sodium hexametaphosphate

TABLE 5 - Fe and TiO_2 in attapulgite HIMS fractions

Sample	Percent Fe	Percent TiO_2
Control	2.18	0.43
30 second non-magnetic	2.10	0.36
1 minute non-magnetic	2.10	0.30
2 minute non-magnetic	2.10	0.23

Discussion - Attapulgite is a common mineral in the fuller's earth clays that occur in south Georgia and north Florida. This absorbent clay is used as a drilling mud, as a carrier for insecticides and fungicides, and as an absorbent for grease, oil, water, and chemicals. According to Oulton (25) more than 90 different grades of fuller's earth are produced. Some of these grades are used for pharmaceuticals, for purifying water and dry-cleaning fluids, and as extenders or fillers for plastic, paint, and putty. The iron content of the attapulgite clays is relatively high and it was hoped that by using high intensity magnetic separation that the iron could be significantly reduced and the color improved. As indicated, the iron content was not reduced significantly so it is assumed that the iron is substituted in the mineral structure where it replaces some of the magnesium. The titanium content was reduced significantly but titanium minerals are present in very small amounts. Therefore, it can be assumed that HIMS as a beneficiation method would not be successful for processing attapulgites.

BALL CLAY

Ball clay is a term used for a secondary or sedimentary clay commonly characterized by the presence of organic matter, high plasticity, high dry strength, long vitrification range, and a light color when fired. Kaolinite is the principal mineral constituent of ball clay (26). Ball clays are primarily marketed to the ceramic industry.

Sample locations -- Paris, Tennessee and Mayfield, Kentucky
Test conditions - Particle size - minus 325 mesh
Canister matrix - Steel wool
Retention time - 30 seconds, 1 minute, 2 minutes
Field strength - 20 kilogauss
Percent solids - 20 - Dispersant - sodium hexametaphosphate

TABLE 6 - Fe, Mn, TiO_2, K, and S in ball clay HIMS fractions

Sample	Percent Fe	Mn	TiO_2	K	S
Control - Tenn.	0.65	0.44	1.57	0.50	0.054
30 second non-magnetic	0.59	0.41	1.44	0.44	0.043
1 minute non-magnetic	0.62	0.37	1.27	0.39	0.034
2 minute non-magnetic	0.63	0.33	1.17	0.35	0.024
Control - Ky.	0.65	0.86	1.43	0.98	0.044
30 second non-magnetic	0.56	0.78	1.23	0.89	0.024
1 minute non-magnetic	0.55	0.72	1.03	0.75	0.022
2 minute non-magnetic	0.49	0.60	0.82	0.72	0.020

Discussion - Ball clays are used in many ceramic applications. Fired color is an important property and thus the iron, titanium, and manganese content are very important because of their effect on fired color. The sulfur content is related to the amount of pyrite in the sample and the potassium content reflects the mica content. As can be seen from the results above and on Figure 3, the ball clay samples can be cleaned up considerably using HIMS as a processing method. A magnetic separator could be installed to beneficiate the ball clays that are shipped in slurry form which would result in a very much improved product that would be more uniform and would fire to a white color. More detailed work with additional samples is recommended.

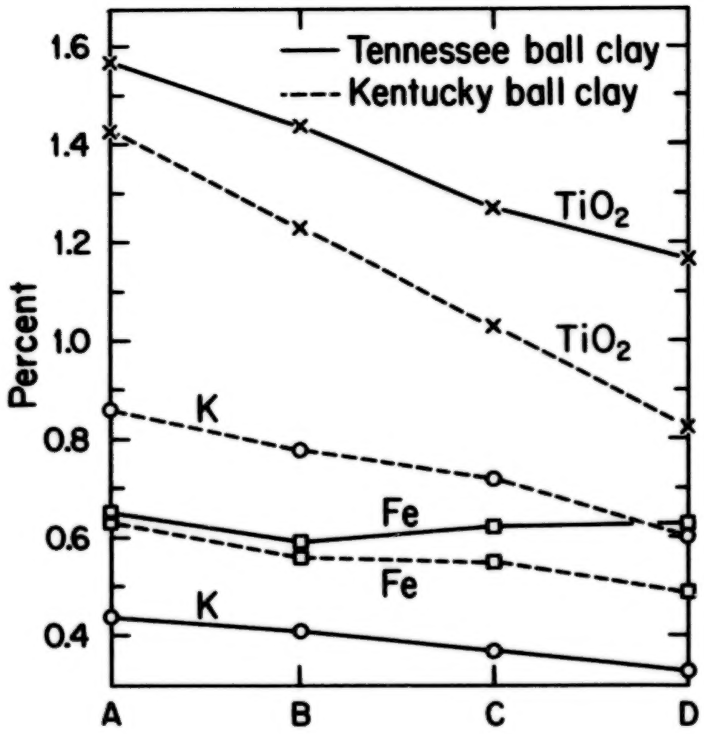


Figure 3 - Effect of retention time on TiO_2, Fe and K content

BARITE

Barite (barium sulfate) is the most common and abundant ore mineral of barium. It is a heavy mineral with a calculated specific gravity of 4.5. The major use for barite is as a weighting agent in drilling fluids used in oil wells. Other uses are in chemicals, glass, and as a filler, pigment, and extender. Major contaminants in many barite ores are iron bearing minerals.

Sample locations - Washington Co., MO; Cartersville, GA; and Battle Mountain, NV.
Test conditions - Particle size - minus 50 mesh for the Missouri and Georgia barite and minus 325 mesh for the Nevada barite.
Canister matrix - Frantz screens for the Missouri and Georgia barite and steel wool for the Nevada barite.
Retention time - 30 seconds, 1 minute, 2 minutes
Field strength - 20 kilogauss
Percent solids - Dispersant - sodium hexametaphospahte

TABLE 7 - Fe in barite HIMS fractions

Sample	Percent Fe
Control - Missouri	1.03
30 second non-magnetic	0.99
1 minute non-magnetic	0.88
2 minute non-magnetic	0.86
Control - Georgia	1.43
30 second non-magnetic	1.18
1 minute non-magnetic	1.09
2 minute non-magnetic	1.06
Control - Nevada	0.24
30 second non-magnetic	0.21
1 minute non-magnetic	0.19
2 minute non-magnetic	0.18

Discussion - Barite when used in glass and as a filler or extender must have a low iron content. Normally a very high quality pure barite is mined for use in glass and for applications that require a white or near white color. Two barites that were selected for this study were relatively high in iron and the third was relatively low. Although the iron percentage was lowered by the HIMS beneficiation the color was not significantly improved. Therefore, HIMS is probably not an economic process to beneficiate barite although further work should be done correlating particle size with iron removal.

BAUXITE

Bauxite - Ore of aluminum which is comprised of one or more aluminum hydroxide minerals gibbsite, boehmite, bayerite, and diaspore along with mineral impurities such as siderite, goethite, hematite, anatase, quartz, and kaolinite.

Sample location - Bauxite, Arkansas
Test conditions - Maximum size of particles in sample - 44 micrometers (325 mesh)
Canister matrix - Stainless steel wool and Frantz screens
Retention time - 30 seconds, 1 minute, 2 minutes
Field strength - 5, 10, 15 and 20 kilogauss
Percent solids - 20
Percent dispersant - 0.6 sodium hexametaphosphate

Discussion - Bauxite is in short supply in the United States and chemical and refractory grade bauxites are in short supply in the world. A maximum of 2 percent iron is allowed for refractory and chemical bauxites. The typical Arkansas bauxites have a range of chemical constituents as follows (27) Al_2O_3 - 45-57%; SiO_2 - 5-24%; Fe_2O_3 - 2-12%; TiO_2 - 1.6-2.4%; loss on ignition 22-28%. High intensity magnetic separation will only remove magnetic and paramagnetic minerals which in the case of the Arkansas bauxite would be siderite, anatase, ilmenite, hematite, and goethite. Chemical and refractory grade bauxites demand a much higher price than aluminum grade bauxite and if our limited supply of domestic bauxite in Arkansas could be converted to refractory and chemical grade it would be much more valuable and would relieve our dependence on foreign sources for these two grades. Table 8 shows the results obtained using a matrix of stainless steel wool and Frantz screens at various field intensities and retention times. Figure 4 and Figure 5 show the results graphically. Figures 6, 7, and 8 are the X-ray diffraction patterns of the control sample, the non-magnetic portion of the sample, and the magnetic portion of the sample. Figure 9 shows the particle size distribution of the non-magnetic and magnetic portion of the sample. What does this all mean?

TABLE 8 - Iron and titanium analyses of Arkansas bauxite HIMS fractions

Sample			Fe total	TiO_2
Control - Arkansas bauxite			7.92%	1.60%
Non-mags. - SSW - 0.5 min.	05 KG		1.43	1.14
Non-mags. - SSW - 0.5 min.	10 KG		1.20	1.06
Non-mags. - SSW - 0.5 min.	15 KG		1.08	0.82
Non-mags. - SSW - 0.5 min.	20 KG		1.05	0.79
Non-mags. - FS - 0.5 min.	05 KG		1.77	1.17
Non-mags. - FS - 0.5 min.	10 KG		1.74	1.24
Non-mags. - FS - 0.5 min.	15 KG		1.46	1.16
Non-mags. - FS - 0.5 min.	20 KG		1.38	1.06
Non-mags. - SSW - 1.0 min.	15 KG		0.86	0.71
Non-mags. - SSW - 1.0 min.	20 KG		0.80	0.62
Non-mags. - SSW - 2.0 min.	20 KG		0.91	0.38
Non-mags. - SSW - 0.5 min.	20 KG	1 pass	1.06	0.61
Non-mags. - SSW - 0.5 min.		2 pass	1.07	0.47
Non-mags. - SSW - 0.5 min.		3 pass	1.07	0.57
Non-mags. - SSW - 0.5 min.		4 pass	1.06	0.56

SSW = Stainless steel wool

FS = Frantz screens

Min = Retention time

KG = Kilogauss

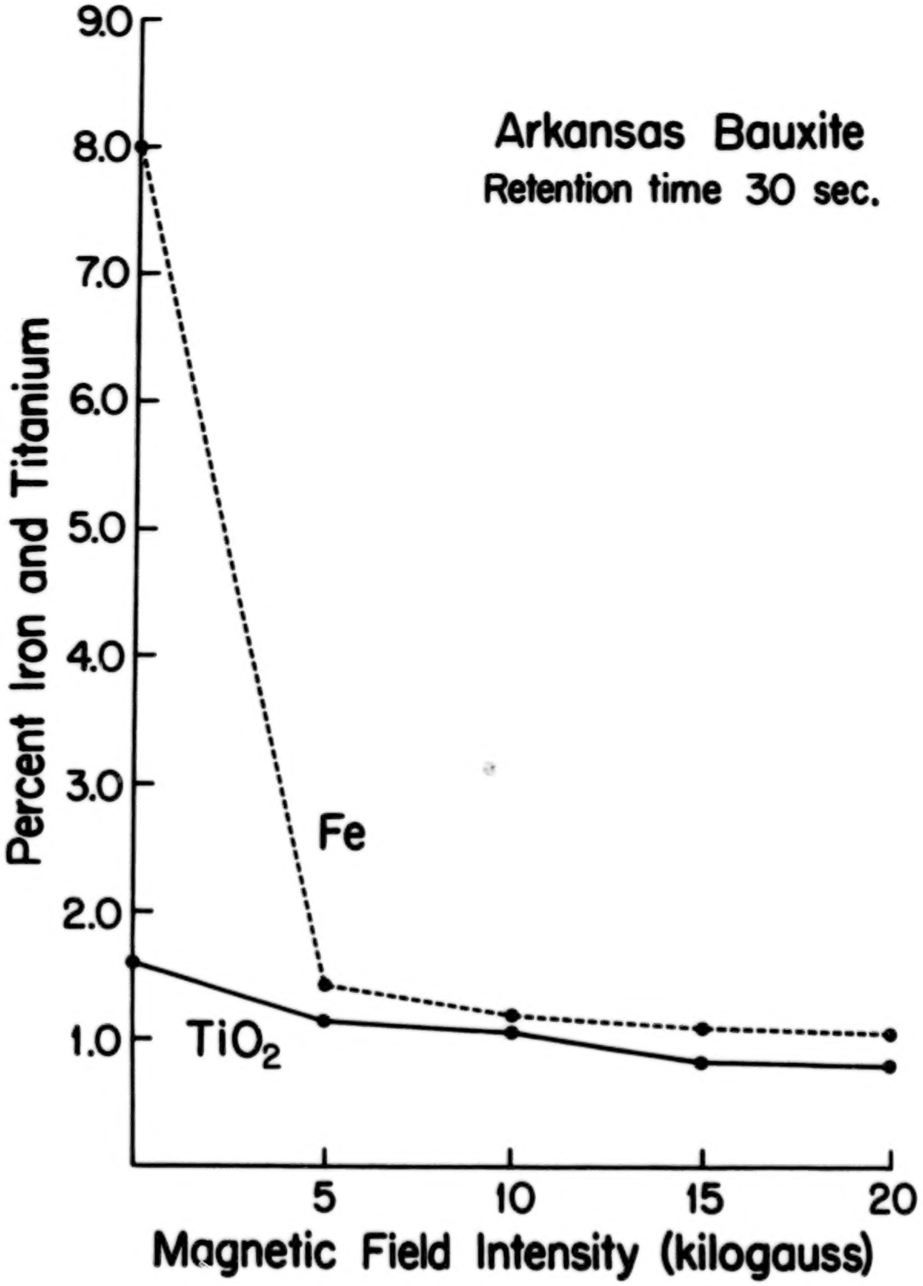


Figure 4 - Arkansas bauxite: percent iron and titanium vs magnetic field intensity

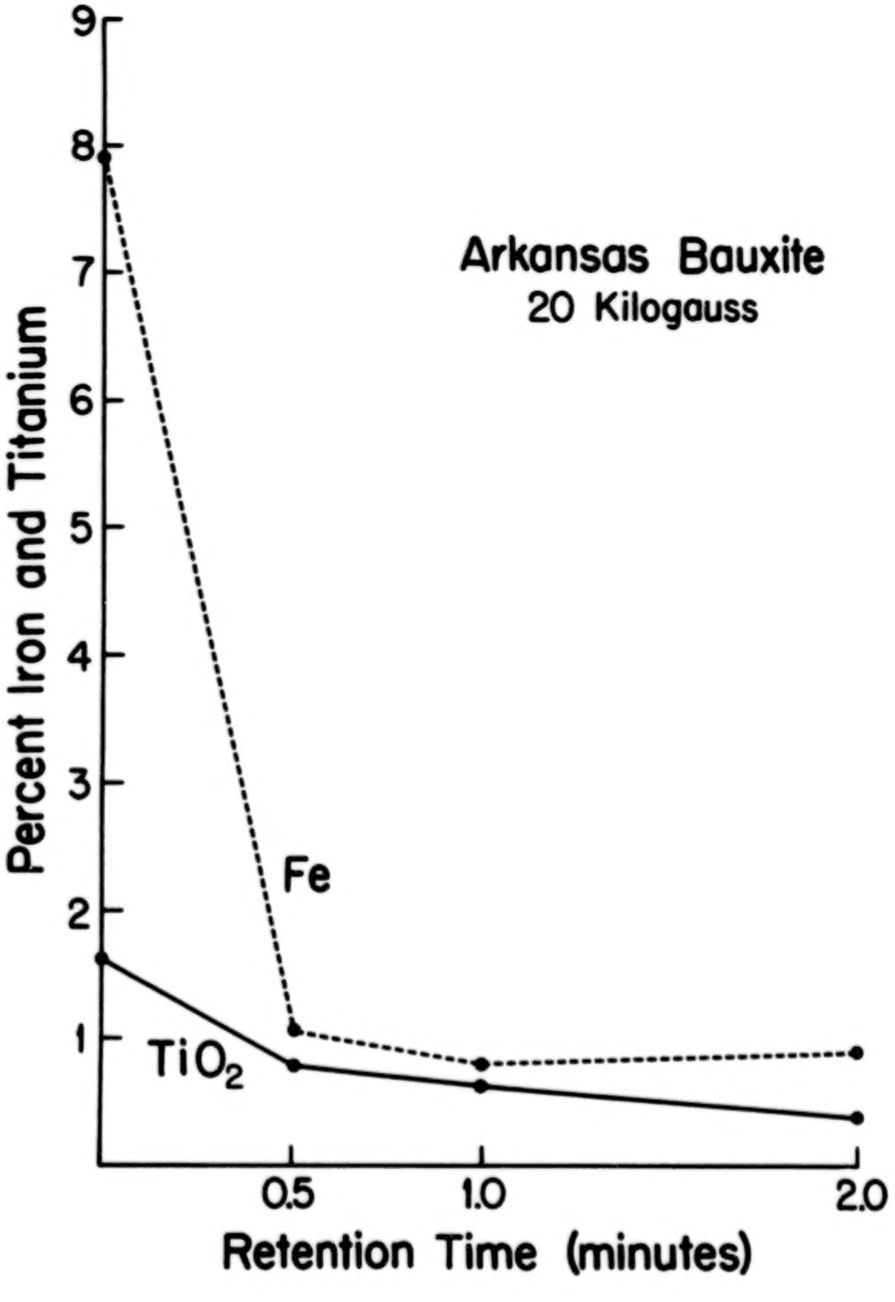


Figure 5 - Arkansas bauxite: percent iron and titanium vs retention time

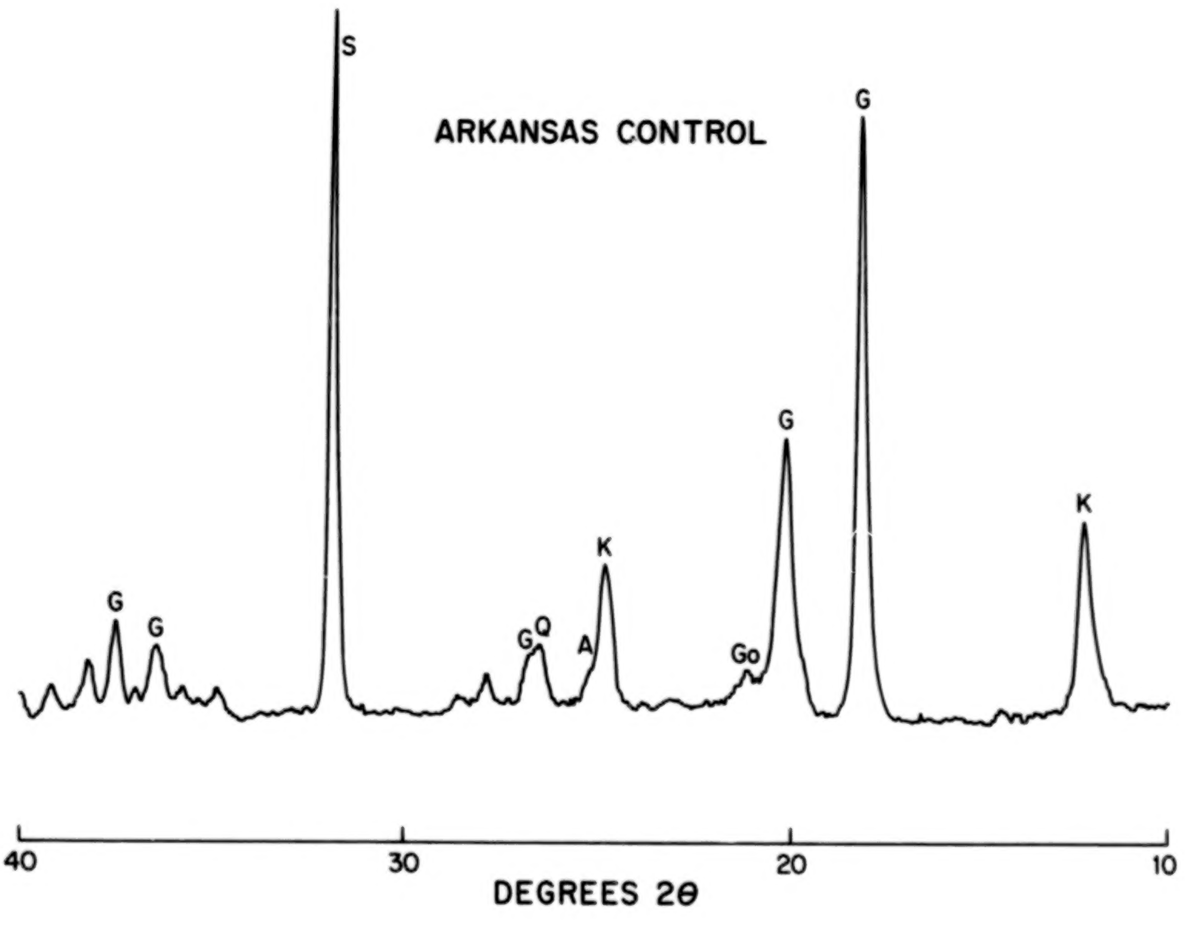


Figure 6 - Arkansas bauxite: X-ray diffraction pattern, control (A-Anatase, G-Gibbsite, Go-Goethite, K-Kaolinite, Q-Quartz, S-Siderite)

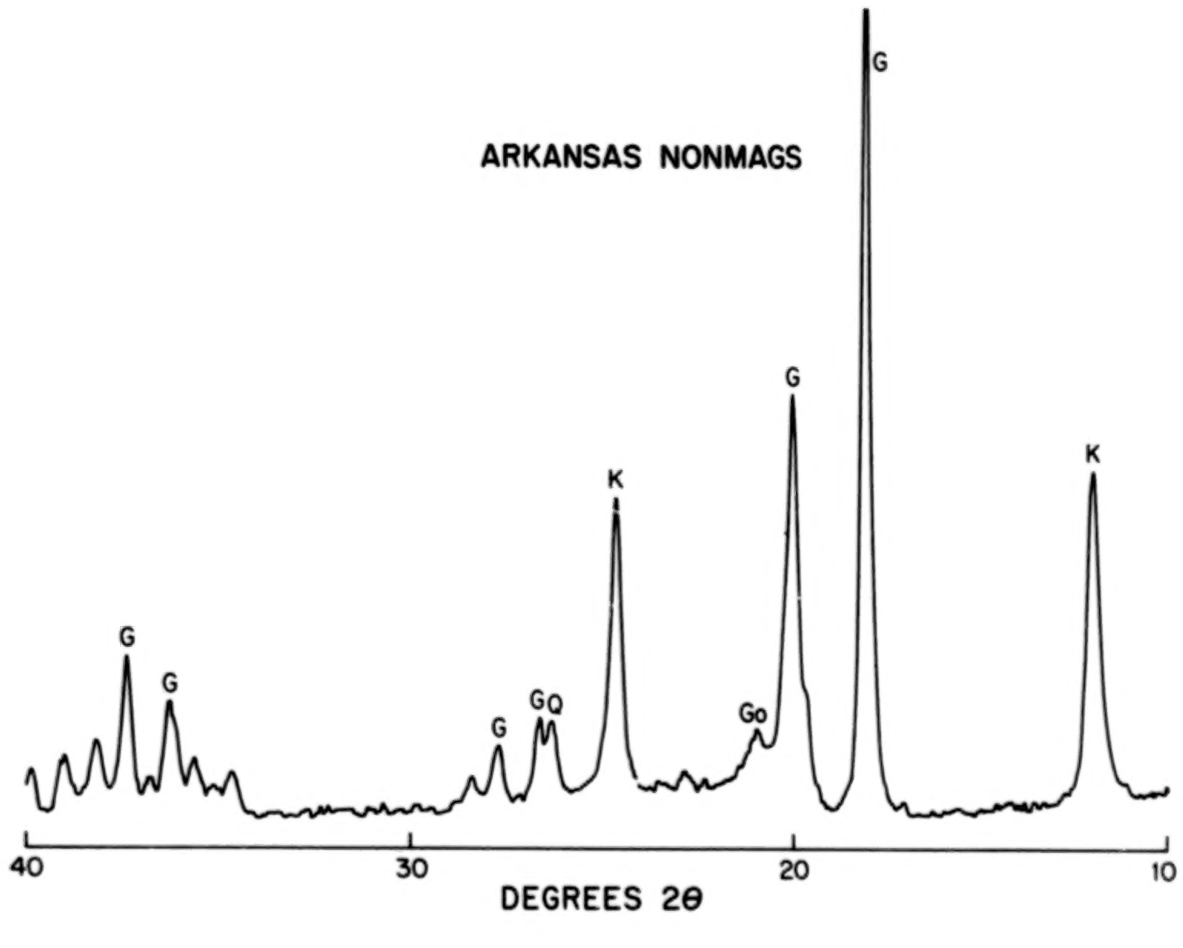


Figure 7 - Arkansas bauxite: X-ray diffraction pattern, nonmags. (G-Gibbsite, Go-Goethite, K-Kaolinite)

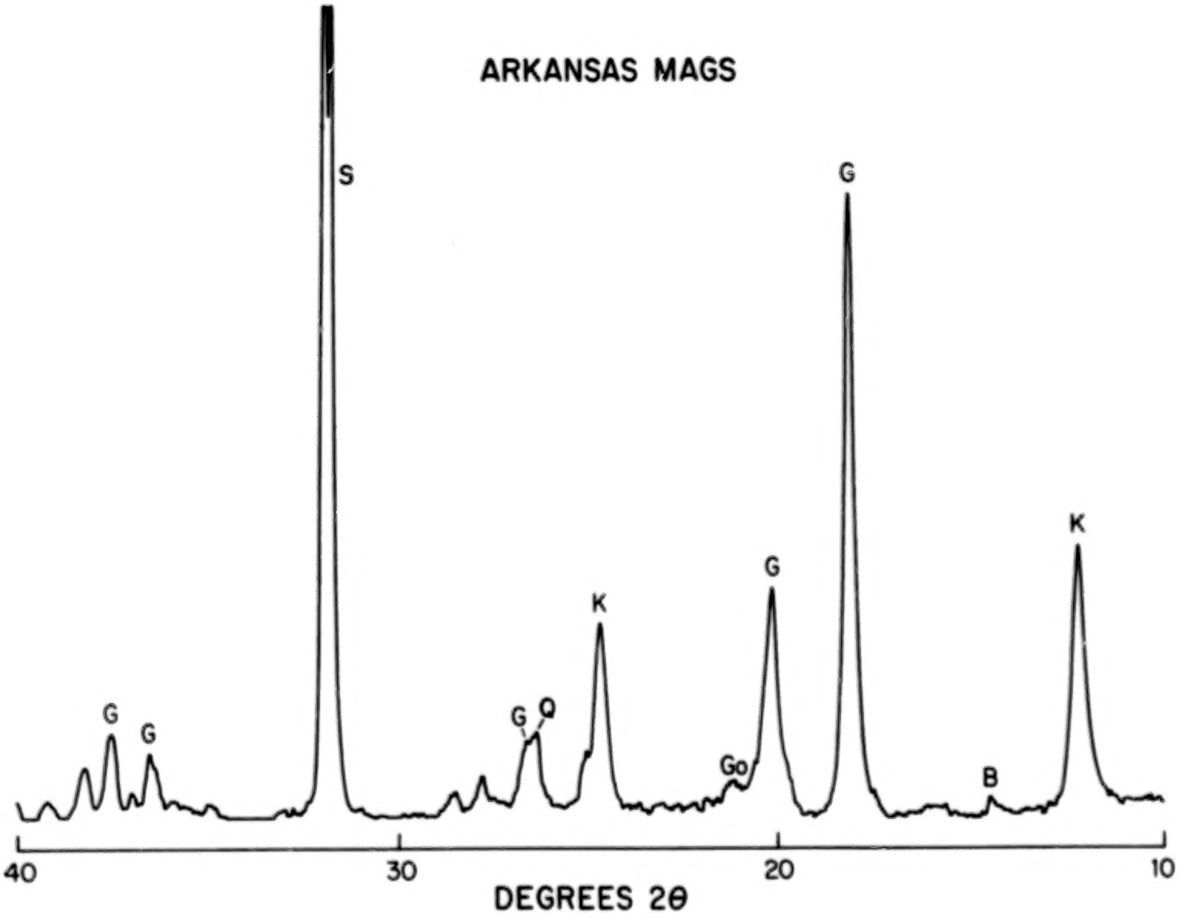


Figure 8 - Arkansas bauxite: X-ray diffraction pattern, mags. (A-Anatase, B-Boehmite, G-Gibbsite, Go-Goethite, Q-Quartz, S-Siderite)

The iron content of the Arkansas bauxite is reduced from 7.92 percent to 1.43 percent at 30 seconds retention time and 5 kilogauss field intensity as shown on Figure 4. Higher field intensity up to 20 kilogauss reduces the iron content to 1.05 percent. The titanium content is reduced from 1.6 percent to 0.79 under similar conditions as shown on Table 8 and Figure 4. Table 8 shows that a matrix of Frantz screens in the canister is not as efficient as the stainless steel wool. Longer retention times can reduce the iron to 0.80 percent and the titanium to 0.38 percent as shown on Table 8 and Figure 5.

The X-ray diffraction pattern of the Arkansas bauxite shown on Figure 6 indicates the major aluminum oxide minerals is gibbsite and the major iron bearing mineral is siderite. Figure 7 is the X-ray pattern of the non-magnetic fraction of the sample which shows that the siderite is completely removed. Figure 8 is the X-ray diffraction pattern of the magnetic fraction and is dominantly siderite. Anatase is the major titanium mineral and it also is removed from the non-magnetic fraction of the sample.

Figure 9 shows the particle size distribution of the control sample and the non-magnetic fraction which shows that the siderite that is removed is relatively coarse because the non-magnetic fraction has a finer particle size distribution than the control. There may also be some physical entrapment of the coarser gibbsite particles in the steel wool matrix.

In conclusion Arkansas bauxite when beneficiated using high intensity magnetic separation with a stainless steel wool matrix, a minimum of 5 kilogauss field strength, and a 30 second retention time results in a product that is low in iron and titanium and would meet the specifications of chemical and refractory grade bauxite. An industrial pilot plant trial is merited based upon these preliminary results.

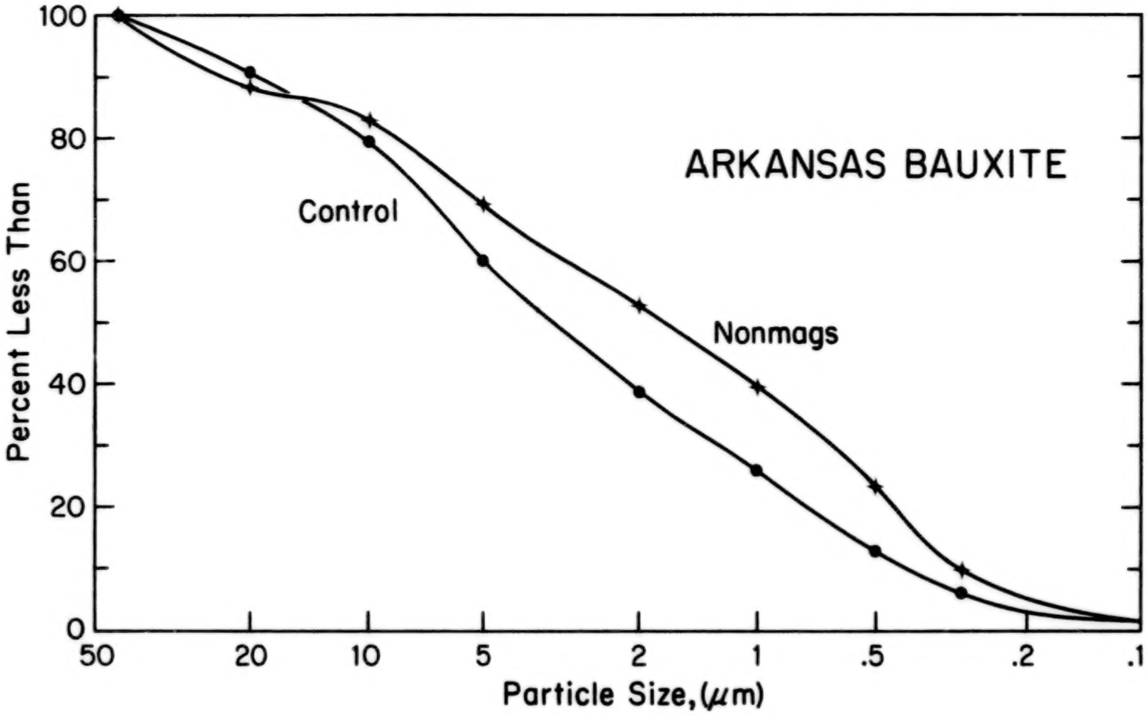


Figure 9 - Arkansas bauxite: particle size distribution curve, control and non-mags.

Sample location - Near Paranam, Surinam
Sample run conditions - Particle size - maximum 44 micrometers (325 mesh)
Canister matrix - Stainless steel wool
Retention time - 30 seconds, 1 minute, and 2 minutes
Field strength - 10 and 20 kilogauss
Percent solids - 20 with 0.6 percent sodium hexametaphosphate dispersant

Discussion - The Surinam bauxite contains gibbsite and boehmite as the major aluminum oxide minerals and hematite and goethite as the major iron bearing minerals (Fig. 10). The typical chemical analyses of the Surinam bauxites are (27) Al_2O_3 - 50-60%; SiO_2 - 2-6%; Fe_2O_3 - 2-15%; TiO_2 - 2-3%; LOl - 29-31%.

Table 9 shows the iron and titanium analyses of the Surinam bauxite control sample and the various non-magnetic fractions run at various field strengths and retention times using stainless steel wool in the matrix. Figure 11 shows a plot of the percent iron and titanium versus retention time at a field strength of 20 kilogauss and Figure 12 is a similar plot at a field strength of 10 kilogauss. Figures 13 and 14 are X-ray diffraction patterns of the non-magnetic and the magnetic fraction of the sample and show that the hematite and goethite are concentrated in the magnetic fraction.

The results indicate that the iron content in the Surinam sample can be reduced from 3.3 percent to 0.75 percent at 30 seconds retention time and 20 kilogauss field strength and the titanium content can be reduced from 1.44 percent to 0.83 percent under the same conditions. With a longer retention time of 2 minutes the iron content can be reduced to 0.64% and the titanium content to 0.64 percent

Figure 15 shows the particle size distribution curves of the control sample and the non-magnetic fraction. This shows that the particle size distribution is very similar and that iron and titanium minerals were removed by magnetic filtration in all size ranges.

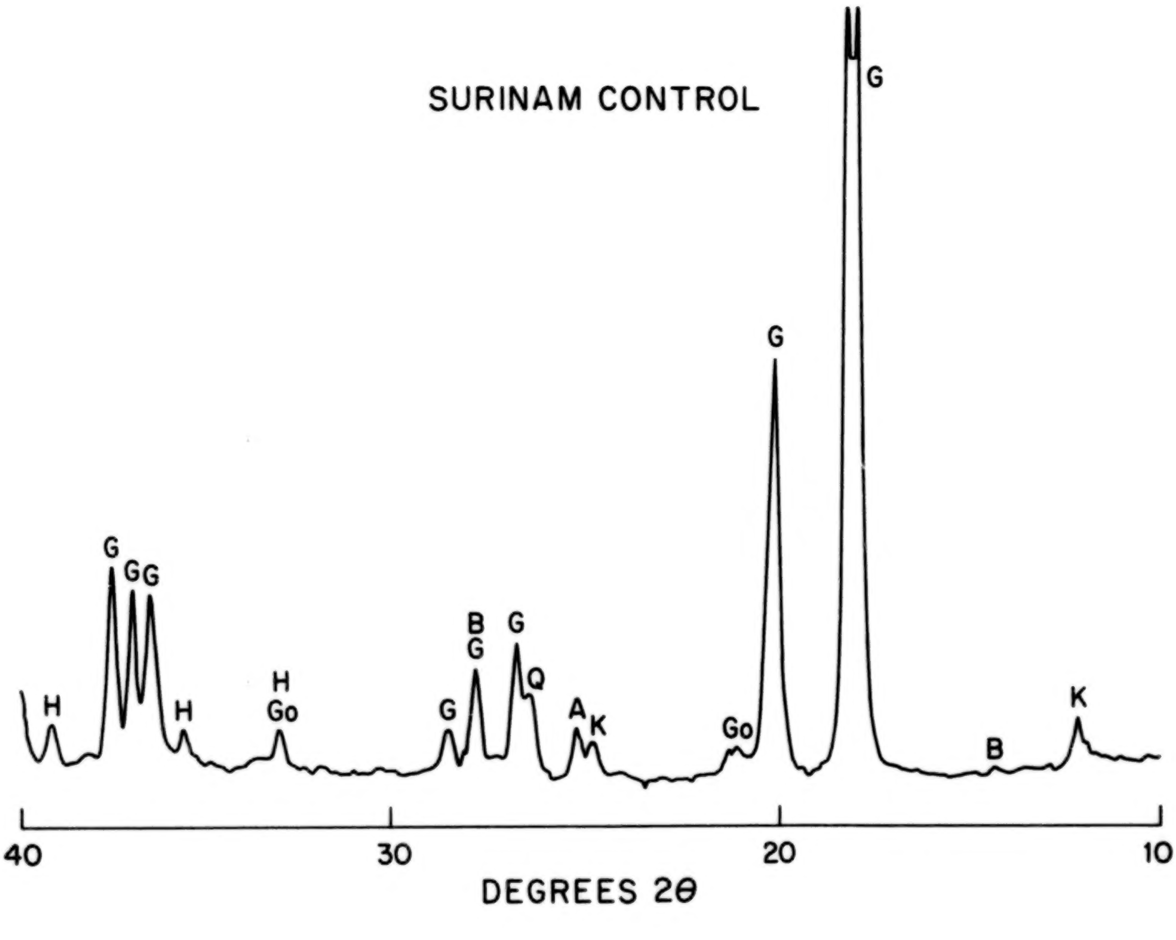


Figure 10 - Surinam bauxite: X-ray diffraction pattern, control. (A-Anatase, B-Boehmite, G-Gibbsite, Go-Goethite, H-Hematite, K-Kaolinite, Q-Quartz)

TABLE 9 - Iron and titanium analyses of Surinam bauxite HIMS fractions

Sample		Fe total	TiO_2
Control - Surinam bauxite		3.30%	1.44%
Non-mags. - SSW - 0.5 min.	20 KG	0.75	0.83
Non-mags. - SSW - 1.0 min.	20 KG	0.66	0.75
Non-mags. - SSW - 2.0 min.	20 KG	0.64	0.64
Non-mags. - SSW - 0.5 min.	10 KG	1.15	0.99
Non-mags. - SSW - 1.0 min.	10 KG	0.90	0.83
Control - 44 - 2 μm		4.33	1.44
Non-mags. - 44 - 2 μm		0.28	0.56
Control - 2 μm		3.68	1.64
Non-mags. - 2 μm		1.78	0.94

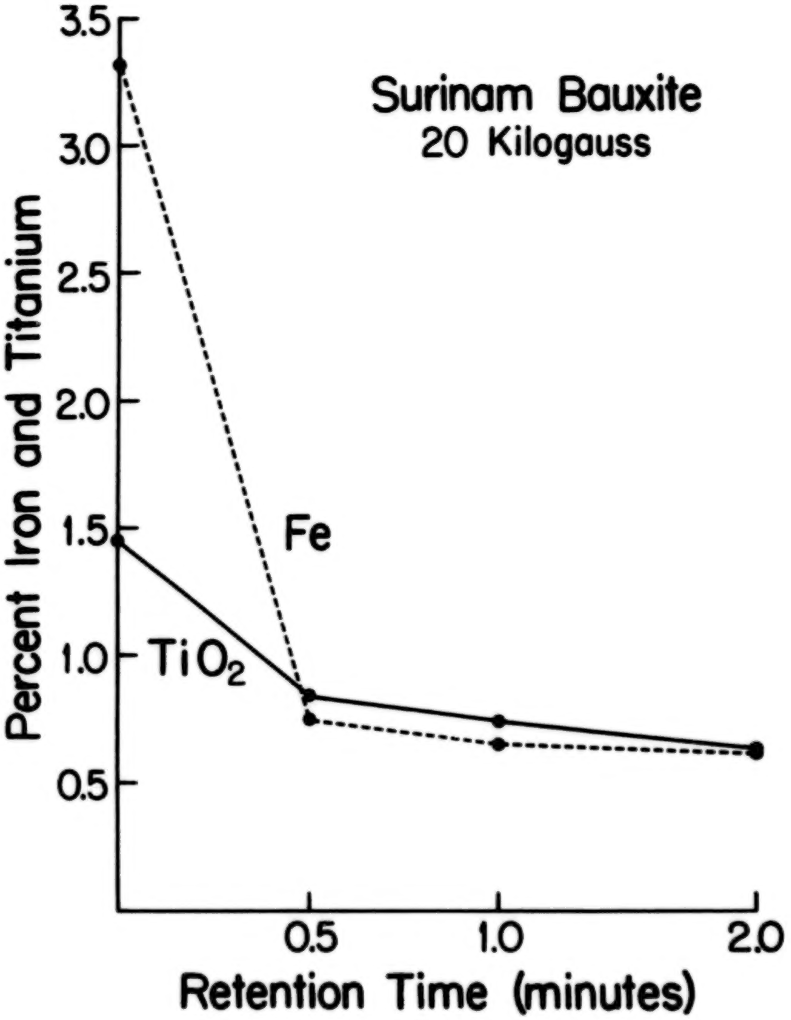


Figure 11 - Surinam bauxite: percent iron and titanium vs retention time, 20 KG.

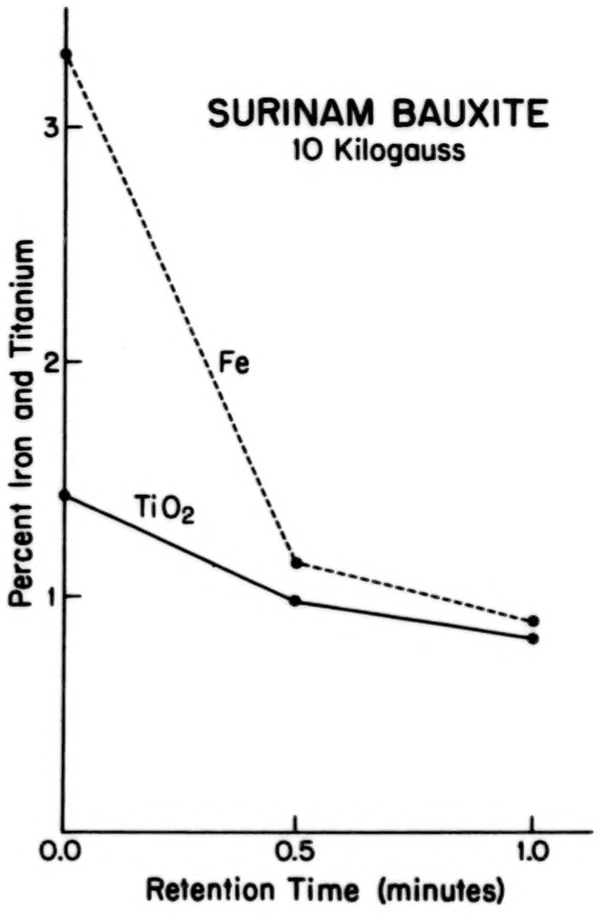


Figure 12 - Surinam bauxite: percent iron and titanium vs retention time, 10 KG.

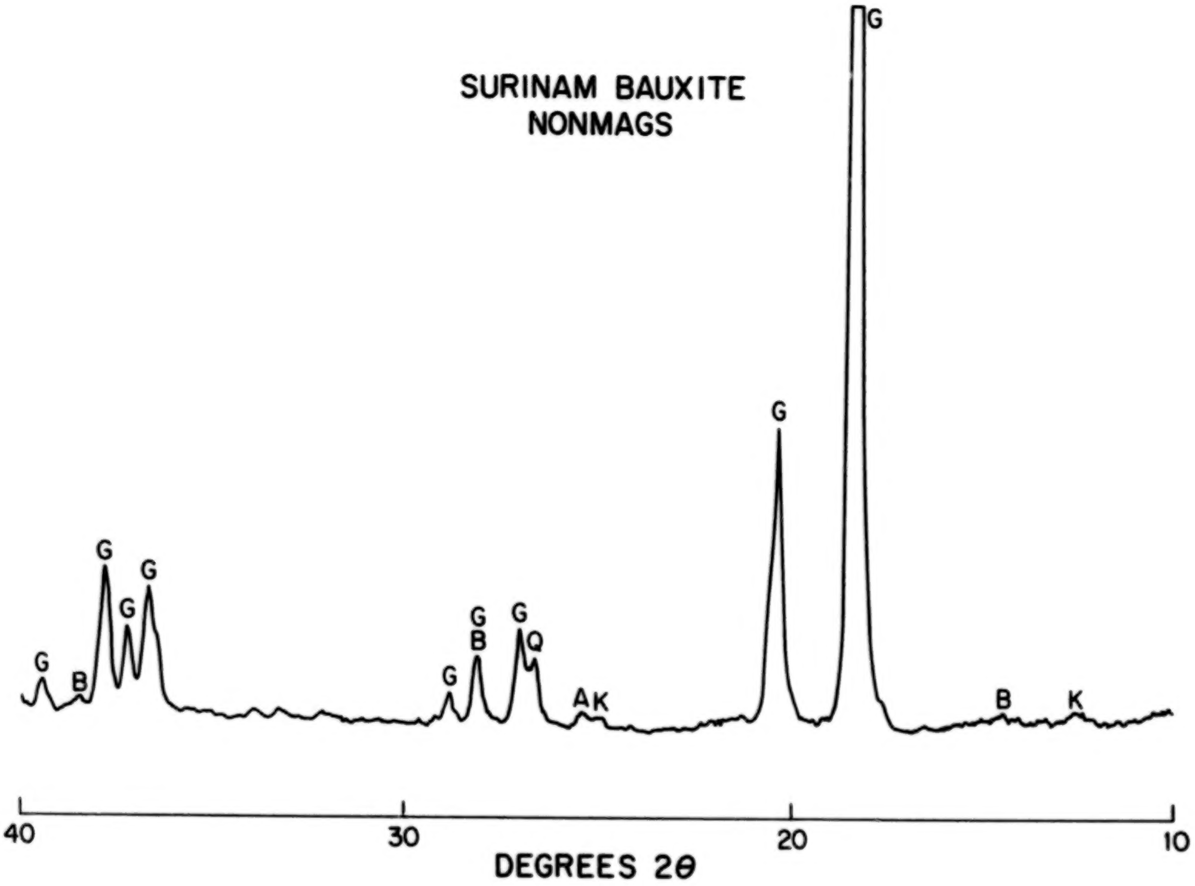


Figure 13 - Surinam bauxite: X-ray diffraction pattern, non-mags.
(A-Anatase, B-Boehmite, G-Gibbsite, K-Kaolinite,
Q-Quartz)

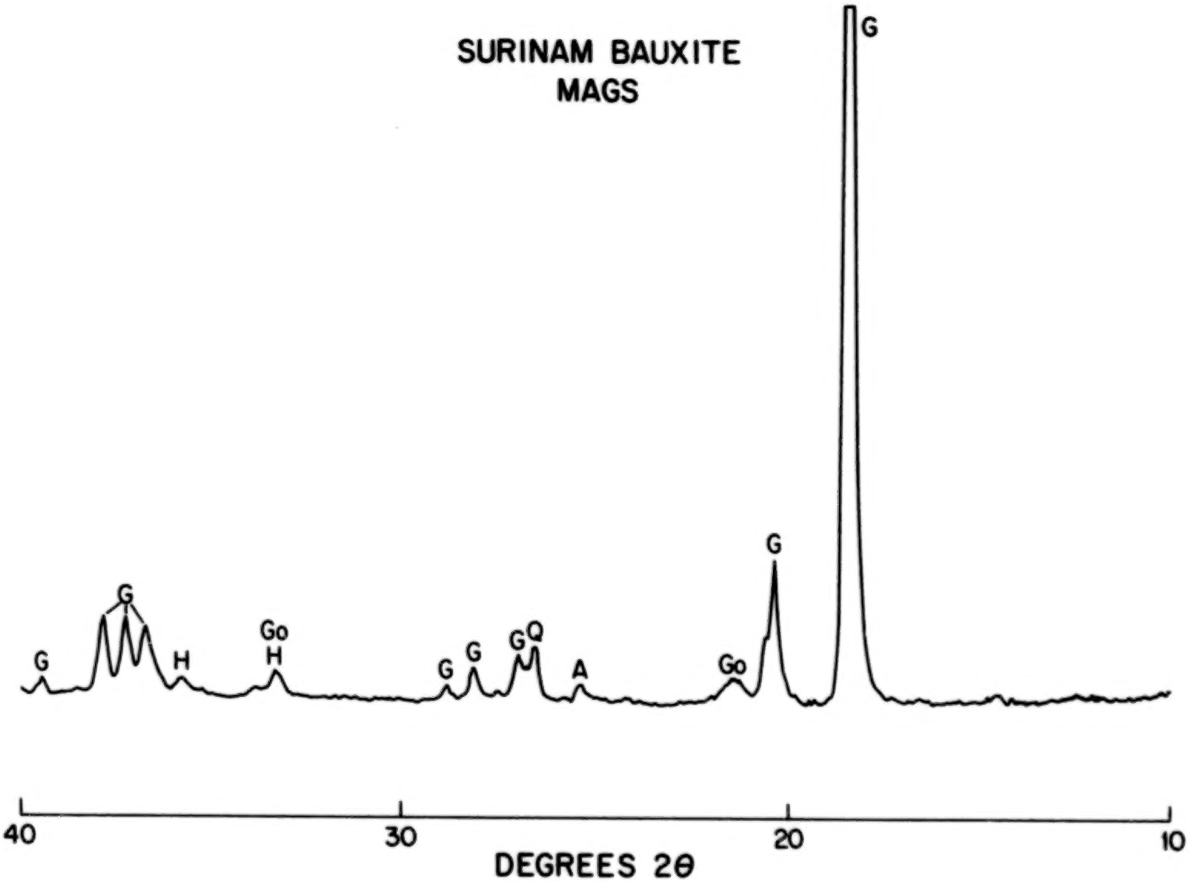


Figure 14 - Surinam bauxite: X-ray diffraction pattern, mags. (A-Anatase, G-Gibbsite, Go-Goethite, H-Hematite)

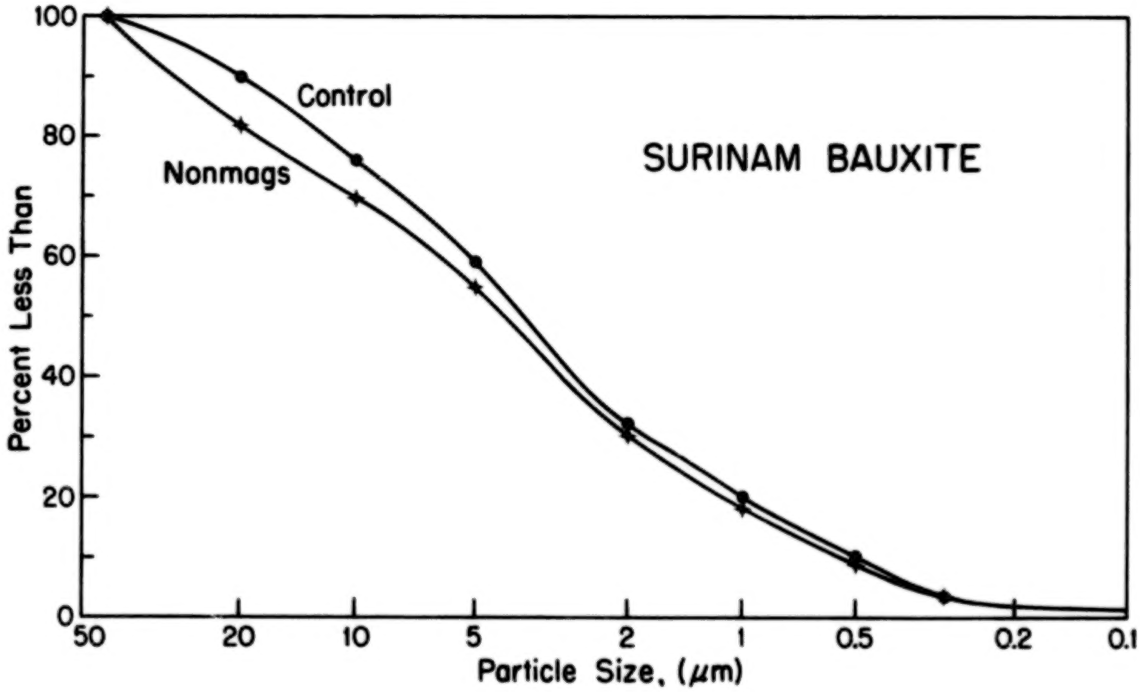


Figure 15 - Surinam bauxite: particle size distribution curve, control and non-mags.

The high intensity magnetic separation process successfully beneficiated the Surinam bauxite to a very low iron and titanium bauxite product and should be commercially investigated.

Sample location - Clarendon, Jamaica
Sample run conditions - Particle size - maximum 44 micrometers (325 mesh)
Canister matrix - Stainless steel wool and Frantz screen
Retention time - 30 seconds, 1 minute and 2 minutes
Field strength - 20 kilogauss
Percent solids - 20 with 0.6 percent sodium hexametaphosphate dispersant

Discussion - The Jamaican bauxite is dark red to brown in color with gibbsite and boehmite as the major aluminum oxide minerals and goethite and poorly crystalline hematite as the major iron minerals (Fig. 16). Typical chemical analyses of Jamaican bauxites are as follows (27). Al_2O_3 - 49-51%; SiO_2 - 0.7-1.6%; Fe_2O_3 - 19-21%, TiO_2 - 2.5-2.7%; LOI - 25-27%.

Table 10 shows the iron and titanium analyses of the Jamaican bauxite sample using stainless steel wool and Frantz screen matrices, 20 kilogauss field strength, and 30 second, 1 and 2 minute retention times. Figure 17 shows a plot of the iron and titanium percentage plotted against retention time at 20 kilogauss capacity. As shown the Jamaican bauxite was not susceptable to a large removal of iron and titanium using HIMS. The best results were a reduction from 10.84 percent iron to 7.88 percent iron and from 1.91 percent titanium to 0.96 percent. Probable reasons for those poor results were:

1. The Jamaican bauxite is very fine grained (Fig. 18).

2. Most of the iron in the Jamaican bauxite is present as finely disseminated hematite and goethite within the grains of gibbsite.

3. Substitution of Fe^{+3} and AL^{+3} is suspected in the structures of the iron and aluminum hydroxide minerals producing mixed, intergrown crystals (28).

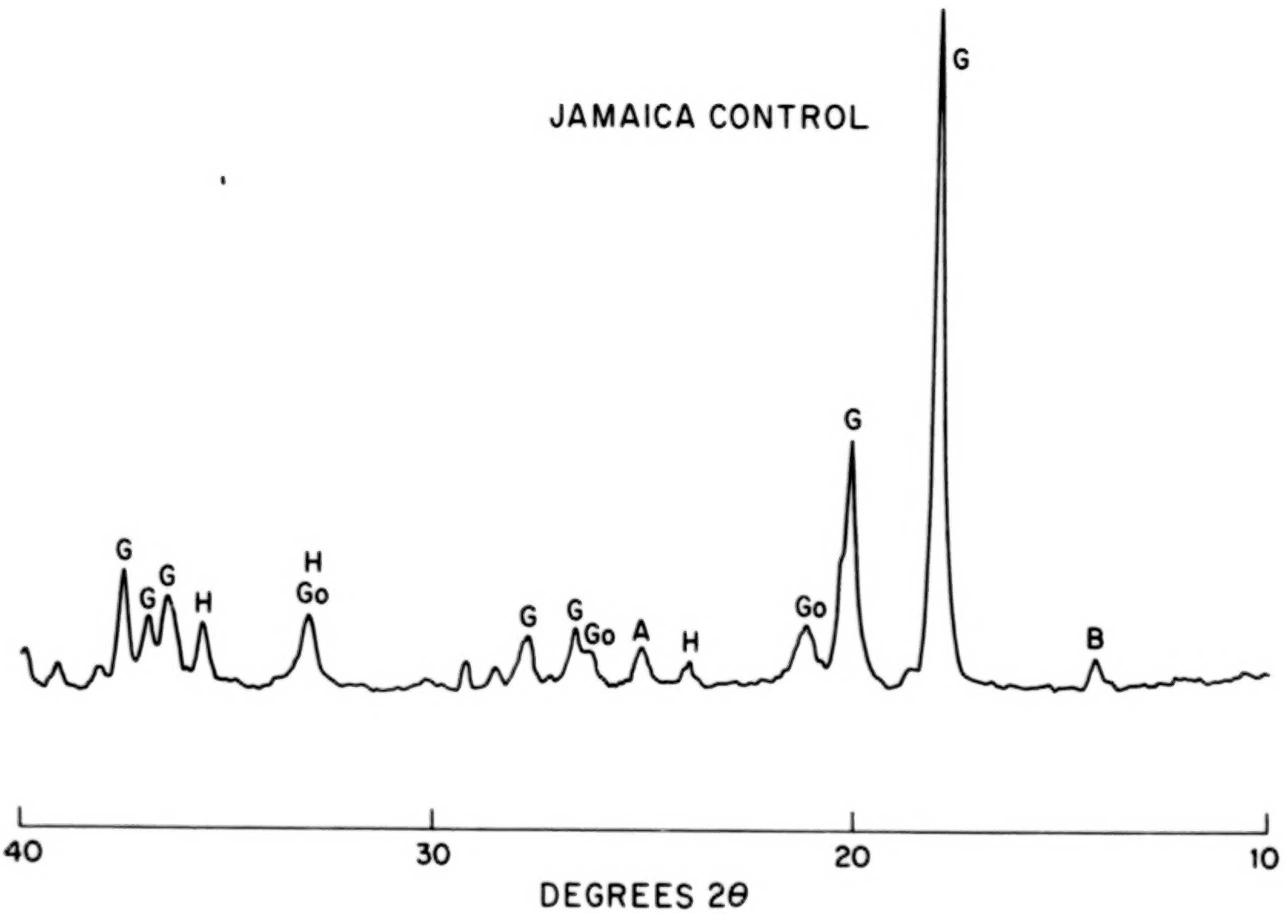


Figure 16 - Jamaica bauxite: X-ray diffraction pattern, control. (A-Anatase, B-Boehmite, G-Gibbsite, Go-Goethite, H-Hematite)

TABLE 10 - Iron and titanium analyses of Jamaica bauxite HIMS fractions

Sample		Fe total	TiO_2
Control - Jamaica bauxite		10.84%	1.91%
Non-mags. - SSW - 0.5 min.	20 KG	8.77	1.53
Non-mags. - SSW - 1.0 min.	20 KG	8.69	0.96
Non-mags. - SSW - 2.0 min.	20 KG	7.88	1.09
Non-mags. - FS - 1.0 min.	20 KG	9.63	1.76
Non-mags. - SSW - 1.0 min.	20 KG *	7.31	0.96

* = Second pass

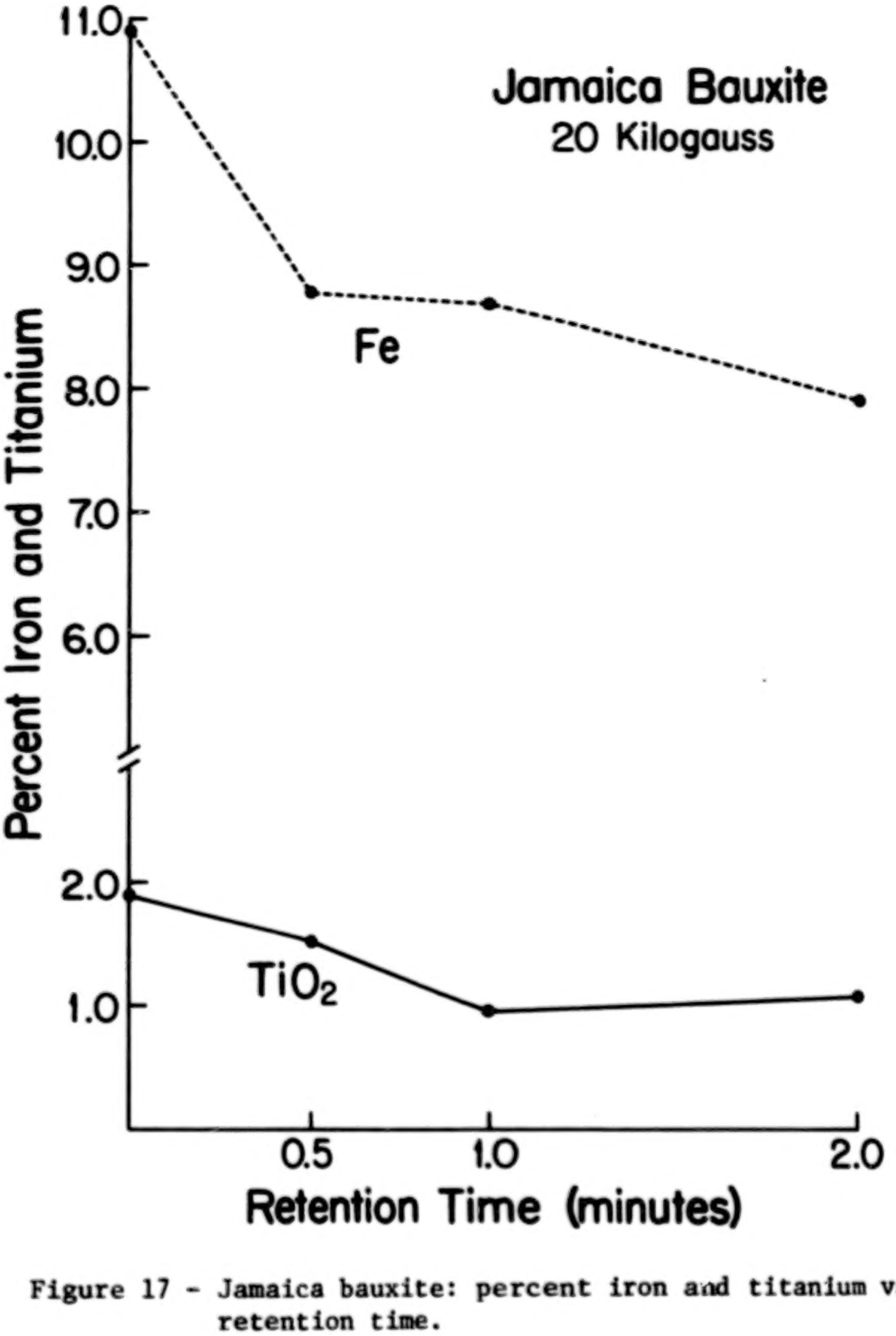


Figure 17 - Jamaica bauxite: percent iron and titanium vs retention time.

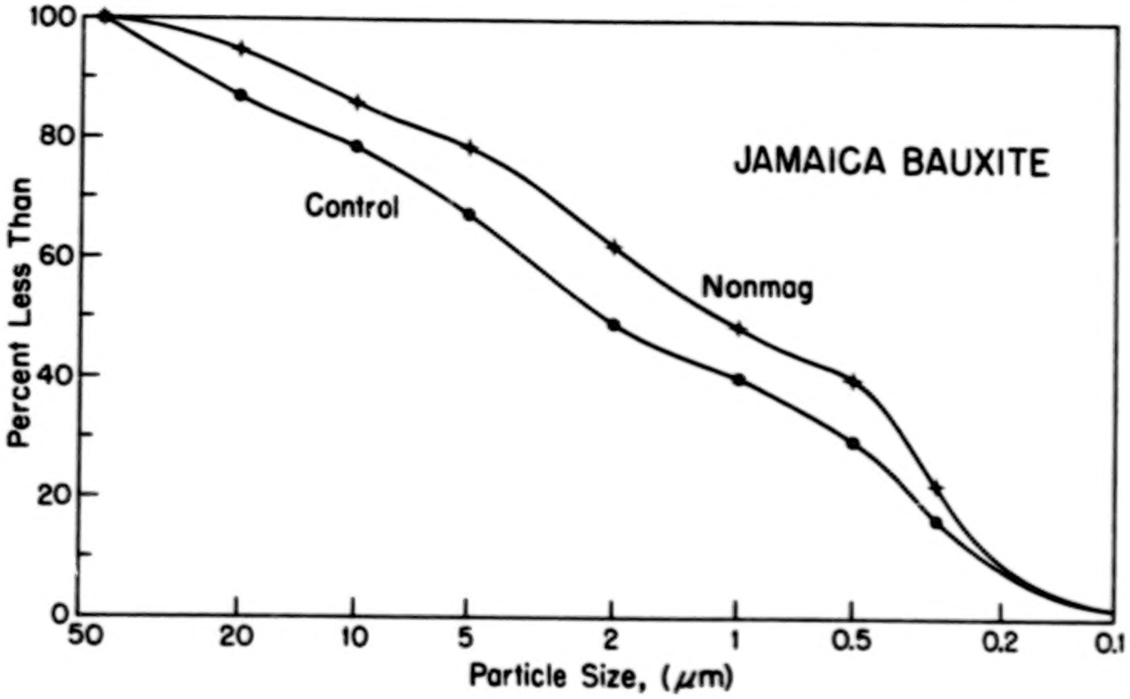


Figure 18 - Jamaica bauxite: particle size distribution curve, control and non-mags.

Sample location - Weipa, Queensland, Australia

Sample run conditions - Particle size - maximum 44 micrometers (325 mesh)

Canister matrix - Stainless steel wool and Frantz screen

Retention time - 30 seconds and 1 minute

Field strength - 20 kilogauss

Percent solids - 20 with 0.6 percent sodium hexametaphosphate dispersant

Discussion - The samples from Weipa, Austraiia contain boehmite and gibbsite as the alumina minerals, hematite and goethite were the major iron bearing minerals, and rutile and anatase were the titanium bearing minerals (Fig. 19). Ranges of major chemical constituents on the Weipa bauxites are: Al_2O_3 - 52-60%; SiO_2 - 2-10%; Fe_2O_3 - 5-13%; TiO_2 - 2.1-3.1%; and LoI - 21-29% (28).

Table 11 shows the iron and titanium analyses of the control samples (a fine and a coarse fraction) showing the retention times, the matrix used, and the field strength for two fine particles size samples and a coarse sample. Figure 20 shows the percent iron and titanium plotted against retention time and indicates very little reduction in iron and titanium of the three samples. Fe^{+3} and Al^{+3} substitution and iron mineral intergrowths with the gibbsite and boehmite are probably the main causes of the poor results.

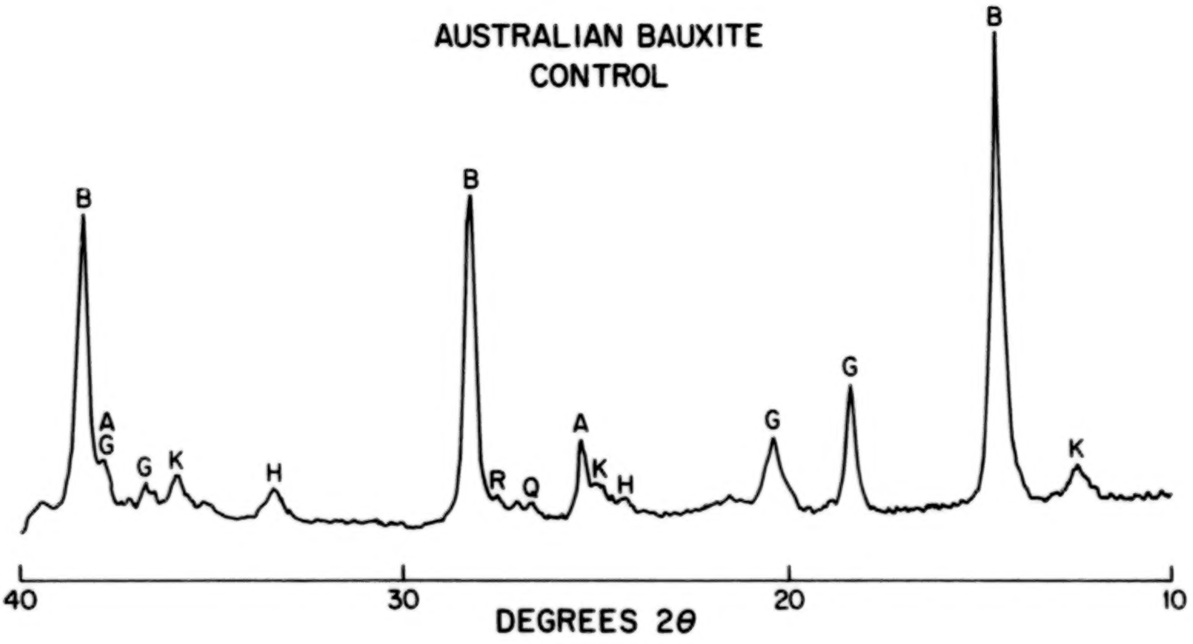


Figure 19 - Australian bauxite: X-ray diffraction pattern, control.

TABLE 11 - Iron and titanium analyses of Australia bauxite HIMS fractions

Sample			Fe total	TiO_2
Control - A - (fines)			5.56%	2.91%
Non-mags A - SSW -	0.5 min.	20 KG	5.04	2.82
Non-mags A	1.0 min.	20 KG	5.13	2.63
Non-mags A - FS -	1.0 min.	20 KG	5.36	2.76
Non-mags A - SSW -	1.0 min.	20 KG *	5.17	2.57
Control - B - (fines)			5.64	2.84
Non-mags B - SSW -	0.5 min.	20 KG	5.27	2.69
Non-mags B	1.0 min.	20 KG	5.31	3.02
Non-mags B - FS -	1.0 min.	20 KG	5.37	2.50
Non-mags B - SSW -	1.0 min.	20 KG *	5.17	2.47
Control - C - (coarse)			5.49	3.03
Non-mags C - FS -	0.5 min.	20 KG	5.37	2.96
Non-mags C	0.5 min.	20 KG *	5.33	2.67
Non-mags C	1.0 min.	20 KG	5.60	2.84
Non-mags C - FS -	0.5 min.	20 KG	----	----
Non-mags C - SSW -	1.0 min.	20 KG	5.27	2.48

SSW = Stainless steel wool
FS = Frantz screens
min = Retention time
KG = Kilogauss

* = Second pass

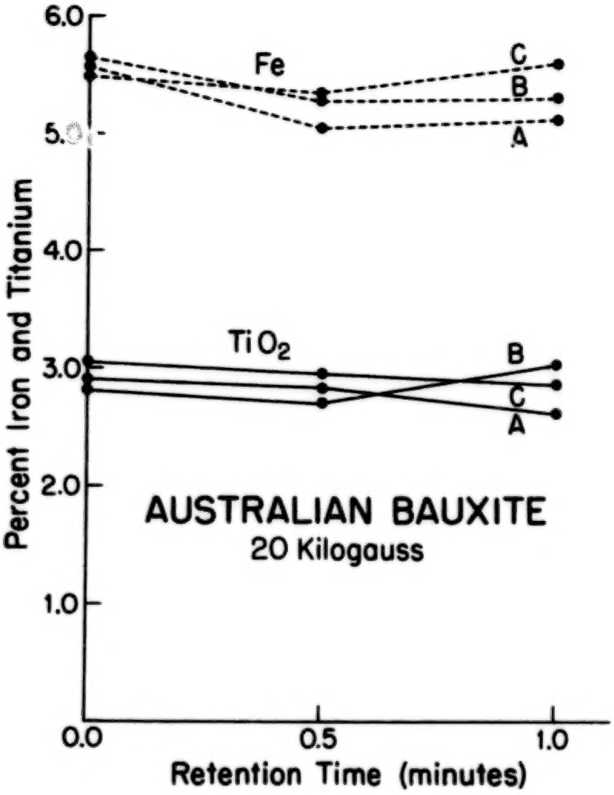


Figure 20 - Australian bauxite: percent iron and titanium vs. retention time.

BENTONITE

Bentonite is a swelling clay that is derived from the alteration of volcanic ash. The major mineral in bentonite is smectite which swells or expands when mixed with water. Bentonites have many uses including drilling muds, foundry sand bond, taconite bond, and many special uses which require a relatively high purity.

Sample locations - Gonzales, Texas: Casper, Wyoming; and Amargosa Valley, Nev.
Test conditions - Particle size - minus 325 mesh
Canister matrix - Steel wool
Retention time - 30 seconds, 1 minute, 2 minutes
Field strength - 20 kilogauss
Percent solids - 5% for Wyoming bentonite } Dispersant sodium
10% for Texas & Nevada bentonite } hexametaphosphate

TABLE 12 - Fe and TiO_2 analyses of bentonite HIMS fractions

Sample	Percent Fe	TiO_2
Control (white) - Texas	0.62	0.14
30 second non-mag.	0.31	0.12
1 minute non-mag.	0.30	0.12
2 minute non-mag.	0.28	0.11
Control (tan) - Texas	3.19	-
30 second non-mag.	3.08	-
1 minute non-mag.	3.03	-
2 minute non-mag.	3.01	-
Control - Wyoming	2.77	-
30 second non-mag.	2.70	-
1 minute non-mag.	2.67	-
2 minute non-mag.	2.69	-
Control - Wyoming	3.81	-
30 second non-mag.*	2.62	-
1 minute non-mag.*	2.63	-
2 minute non-mag.*	2.68	-

* This sample was wet processed and has the coarse fraction removed.

Sample	Percent Fe	TiO_2
Control - Nevada	0.78	-
30 second non-mag.	0.76	-
1 minute non-mag.	0.75	-
2 minute non-mag.	0.72	-

Discussion - Bentonites are generally tan, yellow-green, or gray in color and are used in applications where color is not important. However, some white or light colored bentonites are used in ceramics, suspensions, paper, paint, and other uses where color is an important property. White or light colored bentonites from Texas and Nevada were tested along with a regular drilling mud quality crude bentonite from Wyoming and a Wyoming bentonite which had been wet processed to remove the coarse sand and silt size fraction. Figure 21 shows the results of HIMS treatment on the processed Wyoming bentonite in which over one third of the iron can be removed. For certain applications such as any catalytic use this would be very beneficial. Figure 22 shows the relationship between brightness and retention time of the Nevada and Texas white bentonites. Although the percentage of iron removed as shown by the analyses was not that large, the brightness improvement using HIMS is spectacular. The Nevada brightness was improved from 76.8 to 82.5 and the Texas bentonite from 83 to 93. For pharmaceutical, food processing, and paper additive applications these brightness increases are very significant. From these preliminary results HIMS should be tested further as a process for beneficiating white or light colored bentonites.

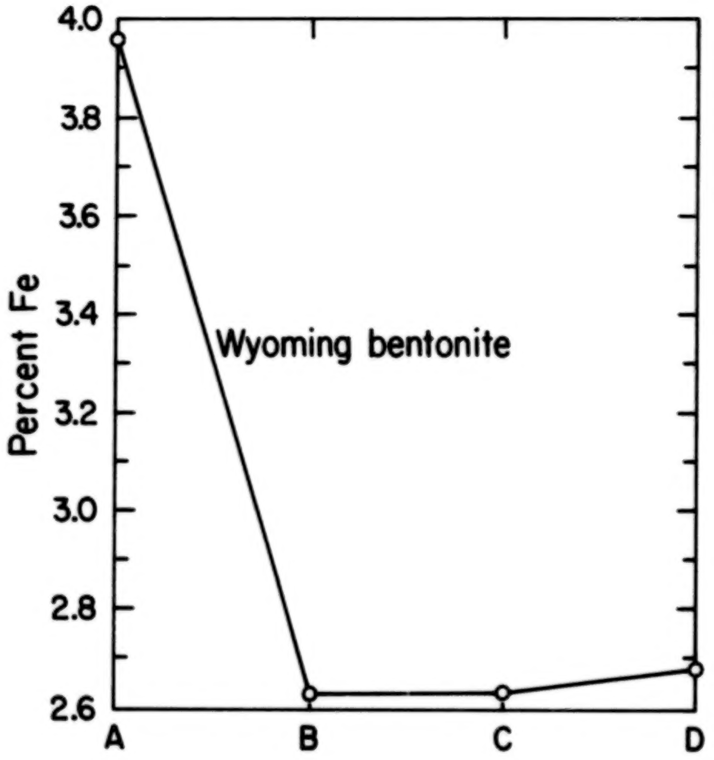


Figure 21 - Relationship between retention time and percent Fe.

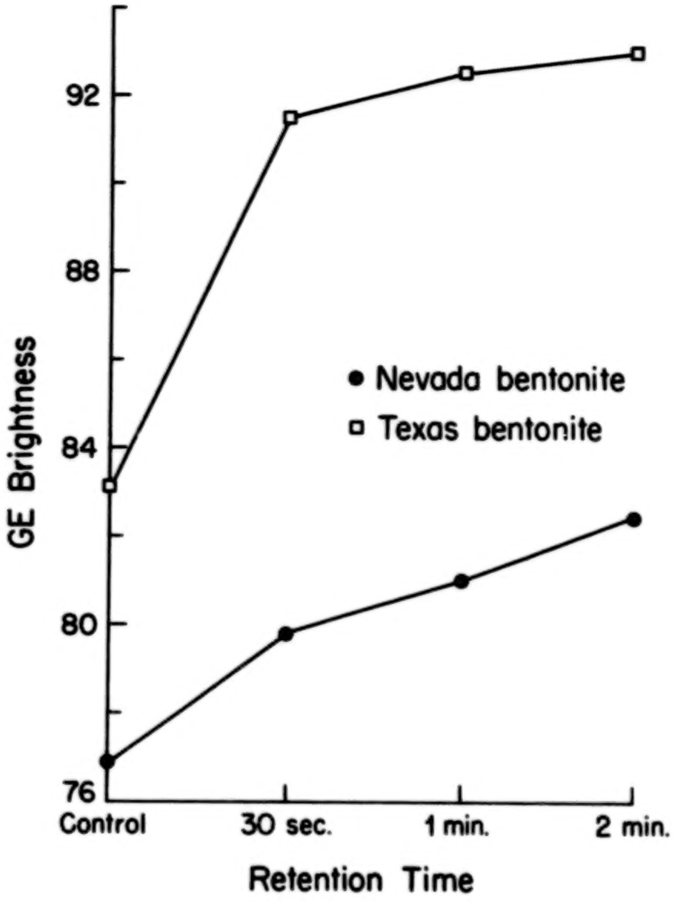


Figure 22 - Relationship between brightness and retention time of Nevada and Texas white bentonites.

CALCITE

Calcite (calcium carbonate) when it is pure and white is used as a filler and extender pigment in many applications including paper, paint, and plastics. A small percentage of iron minerals in the calcite significantly reduces the brightness.

Sample locations - Llano, Texas and Baltimore, Maryland
Test conditions - Particle size - minus 325 mesh
Canister matrix - Steel wool
Retention time - 30 seconds, 1 minute, 2 minutes
Field strength - 20 kilogauss
Percent solids - 20 dispersant sodium hexametaphosphate

TABLE 13 - Fe analyses of calcite HIMS fractions

Sample	Percent Fe
Control - Texas	0.04
30 second non-mag.	0.03
1 minute non-mag.	0.02
2 minute non-mag.	0.02
Control - Maryland	0.097
30 second non-mag.	0.084
1 minute non-mag.	0.082
2 minute non-mag.	0.073

Discussion - Calcium carbonate is the largest tonnage filler used. High quality calcium carbonate is used in paper, paint, rubber and other filler uses and must be very white and usually fine in particle size. The iron percentage, even though very small to begin with, was significantly reduced using HIMS. Figure 23 shows the brightness increase of the two samples indicating a slight improvement in brightness can be achieved using HIMS. HIMS should be studied further as a potential beneficiation process to improve the color of certain calcium carbonates.

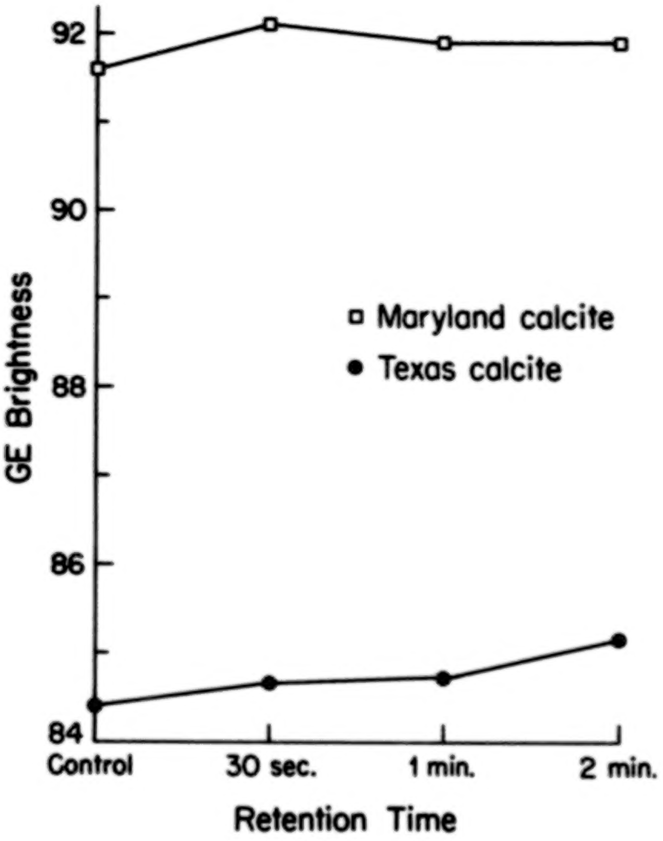


Figure 23 - Brightness of calcite vs. retention time.

DIATOMACEOUS EARTH

Diatomaceous earth (diatomite) is a siliceous, sedimentary rock consisting principally of the fossilized skeletal remains of the diatom, a unicellular aquatic plant. Diatomite has an unusual porous structure and chemical stability which lends it to many applications including filter aids, insulating materials, and fillers and extenders.

Sample locations - Lompoc, California and Lovelock, Nevada
Test conditions - Particle size - minus 40 mesh
Canister matrix - Frantz screens
Retention time - 30 seconds, 1 minute, 2 minutes
Field strength - 20 kilogauss
Percent solids - 20 - dispersant sodium hexametaphosphate

TABLE 14 - Fe and TiO_2 analyses of diatomaceous earth HIMS fractions

Sample	Percent Fe	TiO_2
Control - California	1.05	-
30 second non-mag.	0.86	-
1 minute non-mag.	0.84	-
2 minute non-mag.	0.83	-
Control - Nevada	1.06	0.21
30 second non-mag.	0.92	0.18
1 minute non-mag.	0.78	0.12
2 minute non-mag.	0.64	0.11

Discussion - Diatomaceous earth is used in certain applications where the iron content and the color are very important. Two such uses are as a catalyst support and as a chromatographic support. As can be seen above, the iron content is significantly reduced using HIMS and additional study is recommended.

FELDSPAR

Feldspars are the most abundant minerals in the igneous rocks and occur in a number of mineral forms and compositions. Three common feldspar minerals are orthoclase, a potassium aluminum silicate, albite, a sodium aluminum silicate, and anorthite, a calcium aluminum silicate. Feldspars are used in the glass and ceramic industries so that the iron content is important because of its tinting effect.

Sample location - Bryson City, North Carolina
Test conditions - Particle size - minus 325 mesh
Canister matrix - Steel wool
Retention time - 30 seconds, 1 minute, 2 minutes
Field strength - 20 kilogauss
Percent solids - 20 - dispersant sodium hexametaphosphate

TABLE 15 - Fe analyses of feldspar HIMS fractions

Sample	Percent Fe
Control - North Carolina	0.44
30 second non-mag.	0.28
1 minute non-mag.	0.27
2 minute non-mag.	0.27

Discussion - The iron content of feldspars used in glass and in whitewares must be very low of the order of 0.05 percent. Most feldspars use a flotation process to remove the iron minerals. HIMS removed some iron but not enough to make a glass grade feldspar. HIMS does not look promising as a beneficiation process for removing iron minerals from feldspar.

FLUOSPAR

Fluospar is the commercial name for fluorite, a calcium fluoride. Its valuable properties are due to its content of fluorine and it is the principal commercial source of that element. Fluospar is used in making hydrofluoric acid and its derivatives, in ceramic, steel, and iron foundries as a flux material, and in many other industries. The iron content cannot be over 0.12 for the ceramic uses.

Sample location - Cave-in-Rock, Illinois
Test conditions - Particle size - minus 40 mesh
Canister matrix - Frantz screens
Retention time - 30 seconds, 1 minute, 2 minutes
Field strength - 20 kilogauss
Percent solids - 20 - dispersant sodium hexametaphosphate

TABLE 16 - Fe analyses of fluospar HIMS fractions

Sample	Percent Fe
Control - Illinois	0.32
30 second non-mag.	0.30
1 minute non-mag.	0.29
2 minute non-mag.	0.30

Discussion - HIMS was not successful in reducing the iron content of the fluospar probably because the iron minerals are not liberated by the relatively coarse grinding. If the material were finely pulverized then HIMS using a steel wool matrix might be more successful in reducing the iron content.

GLASS SAND

Glass sand is the commercial term for high silica sand. High silica sand is the principal ingredient used to make glass and is also used in ceramic whitewares, abrasives and as fillers. Quartz (silicon dioxide) is the dominent mineral in glass sand and the iron content for most uses must be exceedingly low of the order of 0.03 or less.

Sample locations - Ottawa, Illinois and Berkeley Springs, W. Va.
Test conditions - Particle size - minus 20 mesh for the sands and minus 325 for the silica flour.
Canister matrix - Frantz screens for the sand samples and steel wool for the silica flour.
Retention time - 30 seconds, 1 minute, 2 minutes
Field strength - 20 kilogauss
Percent solids - 20 - dispersant sodium hexametaphosphate

TABLE 17 - Fe analyses of glass sand HIMS fractions

Sample	Percent Fe
Control - Ottawa	0.033
30 second non-mag.	0.021
1 minute non-mag.	0.019
2 minute non-mag.	0.019
Control - Berkeley Springs	0.043
30 second non-mag.	0.030
1 minute non-mag.	0.024
2 minute non-mag.	0.022
Conrol (silica flour) - Berkeley Springs	0.034
30 second non-mag.	0.015
1 minute non-mag.	0.014
2 minute non-mag.	0.012

Discussion - The iron content in glass sand is extremely critical and must be very low in order not to tint the clear glass. Flotation is a common processing technique to remove iron minerals. The preliminary results shown above indicate that HIMS is a viable method to reduce the iron content and is competitive with flotation as a beneficiation method. Figure 24 shows the brightness increase plotted against retention time for silica flour. Silica flour is used in ceramics, as a filler, and in abrasives. Color is very important and HIMS significantly improved the brightness from 86.5 to 90 which is a very large improvement. Further work is recommended evaluating HIMS as a beneficiation process for glass sand and silica flour.

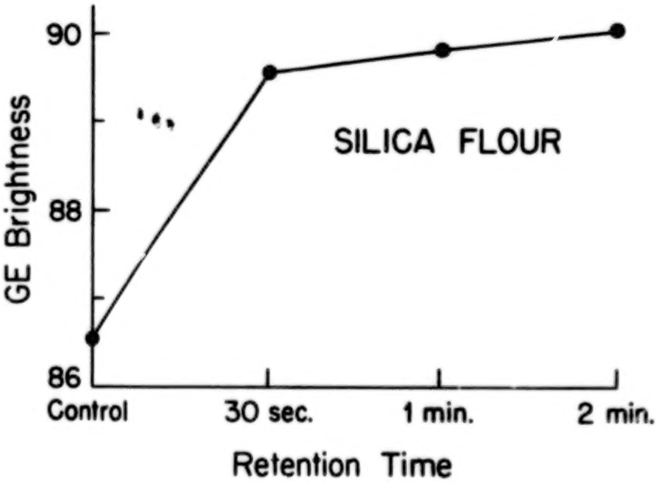


Figure 24 - Brightness of silica flour vs. retention time.

GRAPHITE

Graphite is a black lustrous mineral that is found in laminated, flaky aggregates disseminated in schistose rocks and it also occurs in veins. Graphite is an excellent conductor of heat and electricity and therefore must be very pure for use in most conductive applications.

Sample location - Burnet County, Texas
Test conditions - Particle size - minus 200 mesh
Canister matrix - Steel wool
Retention time - 30 seconds, 1 minute, 2 minutes
Field strength - 20 kilogauss
Percent solids - 20 - dispersant sodium hexametaphosphate.

TABLE 18 - Fe analyses of graphite HIMS fractions

Sample	Percent Fe
Control - Texas	0.46
30 second non-mag.	0.38
1 minute non-mag.	0.40
2 minute non-mag.	0.37

Discussion - Most high quality graphite is imported and it was hoped that the Texas material could be beneficiated to high purity using HIMS. Only a small portion of the iron was removed and it is unlikely that HIMS beneficiation would be successful in reducing the iron content to less than 0.1 percent.

HECTORITE

Hectorite is a lithium smectite and is a special type of bentonite. Commercial quantities are very rare and at present it is mined only in California although there is a small deposit in the Amargosa Valley just across the Nevada line in California. Hectorite is used in some applications where the color and the iron content are important.

Sample locations - Hector, California and Amargosa Valley, California
Test conditions - Particle size - minus 325 mesh
Canister matrix - Steel wool
Retention time - 30 seconds, 1 minute, 2 minutes
Field strength - 20 kilogauss
Percent solids - 5 - Dispersant - sodium hexametaphosphate

TABLE 19 - Fe analyses of hectorite HIMS fractions

Sample	Percent Fe
Control - Amargosa Valley	0.055
30 second non-mag.	0.040
1 minute non-mag.	0.038
2 minute non-mag.	0.037
Control - Hector	0.22
30 second non-mag.	0.14
1 minute non-mag.	0.12
2 minute non-mag.	0.11

Discussion - Hectorite is a very viscous thickening agent and is used in suspensions where color is important. The iron content is reduced using HIMS and the brightness is increased as evidenced by the plot (Fig. 25) of brightness of the Amargosa Valley hectorite which increased from 83.3 to 87 which is a very significant improvement. HIMS has potential application in processing hectorite for special uses where color is important.

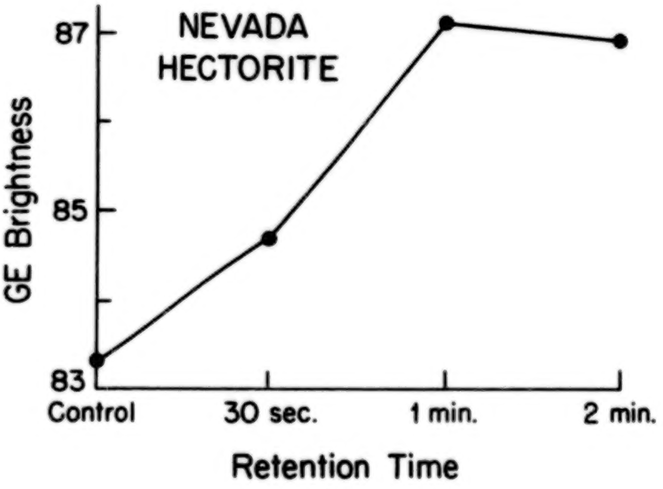


Figure 25 - Brightness of hectorite vs. retention time.

KAOLIN

Kaolin is an industrial rock that is comprised primarily of the mineral kaolinite. It is used as a coating and a filler in paper, and as a filler and extender pigment in paint, rubber, and plastics, and as a primary raw material in ceramics. HIMS has been used very successfully in the kaolin industry in Georgia to improve the brightness (5, 7, 8, 9).

Sample location - Kosse, Texas
Test conditions - Particle size - minus 325 mesh
Canister matrix - Steel wool
Retention time - 30 seconds, 1 minute, 2 minutes
Field strength - 20 kilogauss
Percent solids - 20 - Dispersant - sodium hexametaphosphate

TABLE 20 - Fe, TiO_2, and K analyses of kaolin HIMS fractions

Sample	Percent Fe	TiO_2	K
Control - Kosse	0.58	0.46	0.66
30 seconds non-mag.	0.47	0.40	0.59
1 minute non-mag.	0.42	0.34	0.54
2 minute non-mag.	0.40	0.30	0.48

Discussion - The Texas kaolin was beneficiated using HIMS as shown above and on Figures 26 and 27. The iron, titania, and potassium values were reduced indicating that iron and titanium bearing minerals were removed along with mica. The brightness improved from 67.2 to 74.4 percent. HIMS shows considerable promise as a process that can beneficiate the Kosse, Texas kaolin so that it could be processed into a higher quality product. Further studies are recommended.

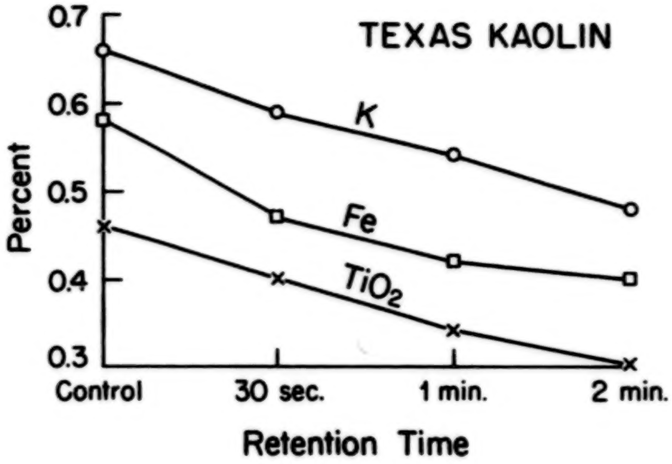


Figure 26 - Relationship between retention time of kaolin and percent Fe, TiO_2, and K.

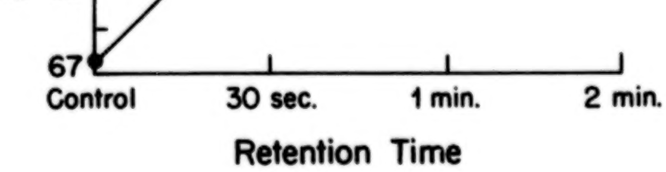


Figure 27 - Brightness of kaolin vs. retention time.

KYANITE

Kyanite is an aluminum silicate mineral that is used in refractories and is an important component in castables and mortars used in acid refractory products. The iron content is important because iron reduces the refractoriness.

Sample location - Washington, Georgia
Test conditions - Particle size - minus 40 mesh
Canister matrix - Frantz screens
Retention time - 30 seconds, 1 minute, 2 minutes
Field strength - 20 kilogauss
Percent solids - 20 - Dispersant sodium hexametaphosphate

TABLE 21 - Fe and TiO_2 analyses of kyanite HIMS fractions

Sample	Percent Fe	TiO_2
Control - Georgia	1.20	1.04
30 second non-mag.	0.26	0.61
1 minute non-mag	0.22	0.41
2 minute non-mag.	0.19	0.39

Discussion - Kyanite must have less than 1 percent Fe_2O_3 and less than 1.2 percent TiO_2. As shown above HIMS beneficiation reduced both iron and titanium substantially and is well within the specifications. It is recommended that further studies of kyanite beneficiation using HIMS be pursued because of the results of this preliminary study. The results are shown graphically on Figure 28.

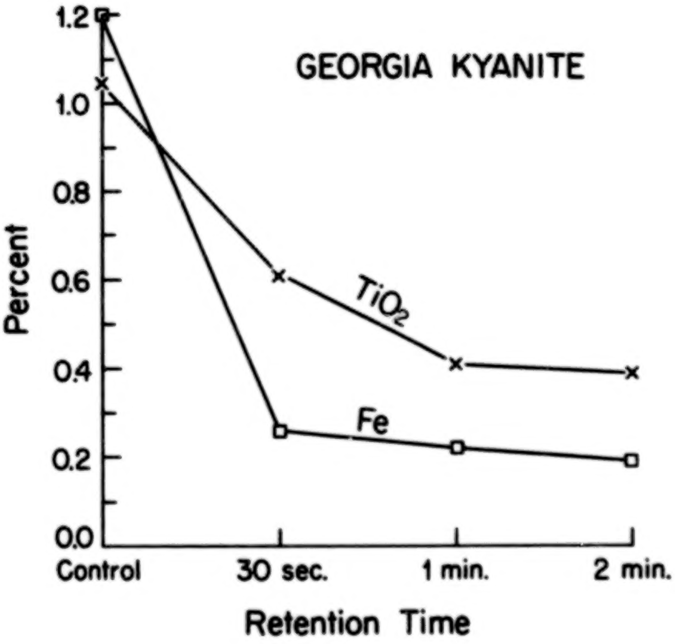


Figure 28 - Relationship between retention time and percent Fe and TiO_2.

MAGNESITE

Magnesite (a magnesium carbonate) is an important ore for magnesium metal and for use in refractories, fluxes, fillers, cements, and other applications. The iron content is particularly important in refractory applications and if present must be beneficiated out.

Sample location - Gabbs, Nevada
Test conditions - Particle size - minus 50 mesh
Canister matrix - Frantz screens
Retention time - 30 seconds, 1 minute, 2 minutes
Field strength - 20 kilogauss
Percent folids - 20 - Dispersed with sodium hexametaphosphate

TABLE 22 - Fe analyses of magnesite HIMS fractions

Sample	Percent Fe
Control (Magnesite) - Nevada	0.26
30 second non-mag.	0.17
1 minute non-mag.	0.17
2 minute non-mag.	0.16

Discussion - The iron content of the Nevada magnesite sample was reduced by approximately one third so HIMS does have promise as a beneficiation technique. The results are encouraging so that further studies on magnesite are recommended.

MICA

Mica is a term which includes several minerals but commercially it refers to the mineral muscovite, a potassium aluminum silicate. Flake mica is used as a filler, as a protection coating on welding electrodes, wires, and cables, and as a functional extender in paints, plastics, and rubber products. Color is an important property and iron bearing minerals are the major colorant.

Sample location - Randolph County, Alabama
Test conditions - Particle size - minus 40 mesh
Canister matrix - Frantz screens
Retention time - 30 seconds, 1 minute, 2 minutes
Field strength - 20 kilogauss
Percent solids - 20 - Dispersant sodium hexametaphosphate

TABLE 23 - Fe analyses of mica HIMS fractions

Sample	Percent Fe
Control (Mica) - Alabama	1.69
30 second non-mag.	1.67
1 minute non-mag.	1.63
2 minute non-mag.	1.64

Discussion - As evidenced by the analyses, HIMS was not successful in reducing the iron content of the mica sample. In view of the results on this sample it does not look as if HIMS would be a method to reduce the iron content of mica deposits unless the mica was a definite mixture of muscovite and biotite (an iron bearing mica) and in this case the biotite could be separated from the muscovite.

NEPHELINE SYENITE

Nepheline Syenite is a rock consisting of feldspars and nepheline, a sodium aluminum silicate, along with small amounts of other accessory minerals. The high quality nepheline syenite is used as a glass and ceramic raw material so therefore must be relatively free of iron bearing minerals.

Sample location - Blue Mountain, Ontario
Test conditions - Particle size - minus 200 mesh
Canister matrix - Frantz screens
Retention time - 30 seconds, 1 minute, 2 minutes
Field strength - 20 kilogauss
Percent solids - 20 - Dispersant - sodium hexametaphosphate

TABLE 24 - Fe and TiO analyses of nepheline syenite HIMS fractions

Sample	Percent Fe	TiO_2
Control (Nepheline) - Canadian	0.052	0.21
30 second non-mag.	0.04	0.09
1 minute non-mag.	0.038	0.05
2 minute non-mag.	0.035	0.07

Discussion - The iron and titanium content of the nepheline syenite is substantially reduced by the HIMS process. Therefore because the iron and titanium content are the major deleterious constituents and the HIMS process appears to work further study is recommended. Arkansas nepheline syenite is a high iron material and a study is recommended using HIMS to beneficiate this material to see if it can be processed to meet the stringent specifications for glass and ceramics.

NOVACULITE

Novaculite is a fine grained siliceous rock which is used as a filler and abrasive. Color is important in its use as a filler.

Sample location - Malvern, Arkansas
Test conditions - Particle size - minus 325 mesh
Canister matrix - Steel wool
Retention time - 30 seconds, 1 minute, 2 minutes
Field intensity - 20 kilogauss
Percent solids - 20 - Dispersant - sodium hexametaphosphate

TABLE 25 - Fe analyses of novaculite HIMS fractions

Sample	Percent Fe
Control (novaculite) - Arkansas	0.31
30 second non-mag.	0.15
1 minute non-mag.	0.084
2 minute non-mag.	0.046

Discussion - The iron content of the novaculite sample was very much reduced. The brightness of the sample as plotted against retention time is shown on Figure 29. HIMS beneficiation successfully reduced the iron to a low level and increased the brightness four percentage points which is very significant. This process should be evaluated further and has excellent potential for use in novaculite processing.

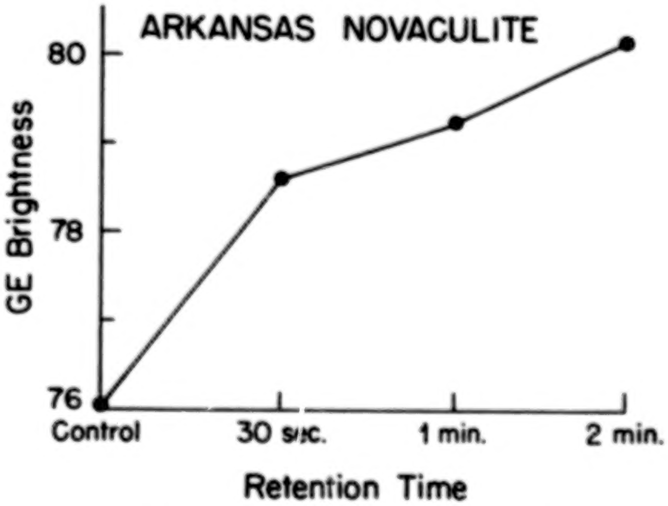


Figure 29 - Brightness of novaculite vs. retention time.

OLIVINE

Olivine is a mafic mineral group name which is comprised of two end member minerals; fayalite, an iron silicate, and forsterite, a magnesium silicate. The magnesium silicate member, forsterite, is used as a refractory material and as a special sand in certain foundry molds and cores. In both of these applications the iron content must be minimal.

Sample location - Asheville, North Carolina
Test conditions - Particle size - minus 200 mesh
Canister matrix - Steel wool
Retention time - 30 seconds, 1 minute, 2 minutes
Field strength - 30 kilogauss
Percent solids - 20 - Dispersant - sodium hexametaphosphate

TABLE 26 - Fe and TiO_2 analyses of olivine HIMS fractions

Sample	Percent Fe	TiO_2
Control (Olivine) - No. Carolina	5.69	0.092
30 second non-mag.	5.36	0.038
1 minute non-mag.	5.07	0.041
2 minute non-mag.	4.66	0.040

Discussion - The iron content of the olivine was only slightly reduced indicating that the iron in the sample is in the olivine mineral structure where it substitutes directly for the magnesium atom. The titanium content is very low in the sample and over half is removed but this is not significant because of the very low value in the control sample. HIMS as a beneficiation method for the North Carolina olivine does not show much promise.

PYROPHYLLITE

Pyrophyllite is an aluminum silicate which is used mainly for refractory purposes but some is also used as a filler. The iron content is therefore very important for both of these applications.

Sample location - Robbins, North Carolina
Test conditions - Particle size - minus 40 mesh
Canister matrix - Frantz screens
Retention time - 30 seconds, 1 minute, 2 minutes
Field strength - 20 kilogauss
Percent solids - 20 - Dispersant - sodium hexametaphosphate

TABLE 27 - Fe analyses of pyrophyllite HIMS fractions

Sample	Percent Fe
Control (pyrophyllite) - No. Carolina	0.32
30 second non-mag.	0.29
1 minute non-mag.	0.30
2 minute non-mag.	0.31

Discussion - HIMS did not remove any iron from the pyrophyllite. In all probability the iron minerals are fine particle size and the sample was relatively coarse so the iron minerals were not liberated.

PHOSPHATE SLIMES

Phosphate slimes are the fine particle size rejects from the flotation process which contain phosphate minerals and iron bearing clay minerals, illite and smectite. It was hoped that HIMS could be used to separate the valuable phosphate fines from the clay minerals.

Sample location - Lakeland, Florida
Test conditions - Particle size - minus 325 mesh
Canister matrix - Steel wool
Retention time - 30 seconds, 1 minute, 2 minutes
Field strength - 20 kilogauss
Percent solids - 10 - no dispersant

TABLE 28 - Fe analyses of phosphate slime HIMS fractions

Sample	Percent Fe
Control (phosphate slime)	1.44
30 second non-mag.	1.46
1 minute non-mag.	1.47
2 minute non-mag.	1.39

Discussion - As evidenced by the iron analyses of the various non-magnetic fractions HIMS beneficiation was not successful in separating the iron bearing clays from the phosphate. Further testing is not recommended on the basis of these preliminary results.

SAPONITE

Saponite is a hydrated magnesium silicate and is a member of the smectite family of minerals. Iron substitutes for magnesium in the mineral structure, and also there are iron bearing accessory minerals in the clay which if removed would make a much cleaner product that could be used in ceramics and as a filler.

Sample location - Amargosa Valley, Nevada
Test conditions - Particle size - minus 325 mesh
Canister matrix - Steel wool
Retention time - 30 seconds, 1 minute, 2 minutes
Field strength - 20 kilogauss
Percent solids - 5 - Dispersant - sodium hexametaphosphate

TABLE 29 - Fe analyses of saponite HIMS fractions

Sample	Percent Fe
Control (saponite) - Nevada	1.70
30 second non-mag.	1.43
1 minute non-mag.	1.41
2 minute non-mag.	1.38

Discussion - Although the iron content in the saponite sample was reduced, the percentage reduction was not significant and very little color improvement was noted. Therefore, HIMS is not recommended as a potential beneficiation process for treating saponite.

SEPIOLITE

Sepiolite is a hydrated magnesium silicate that is used for special drilling muds and if the color is white or near white, can be used in pharmaceutical suspensions, as a filler, and as an additive in special paper coating formulations.

Sample location - Amargosa Valley, Nevada
Test conditions - Particle size - minus 325 mesh
Canister matrix - Steel wool
Retention time - 30 seconds, 1 minute, 2 minutes
Field strength - 20 kilogauss
Percent solids - 5 Dispersant - sodium hexametaphosphate

TABLE 30 - Fe and TiO_2 analyses of sepiolite HIMS fractions

Sample	Percent Fe	TiO_2
Control (sepiolite) - Nevada	0.62	0.11
30 second non-mag.	0.54	0.09
1 minute non-mag.	0.50	0.08
2 minute non-mag.	0.46	0.06

Discussion - The iron and titanium content of the sepiolite were reduced by the HIMS process but not very much. A slight improvement in brightness of two percent is shown on Figure 30. The improvement in color is marginal and therefore HIMS does not have much potential as a beneficiation technique for processing sepiolite.

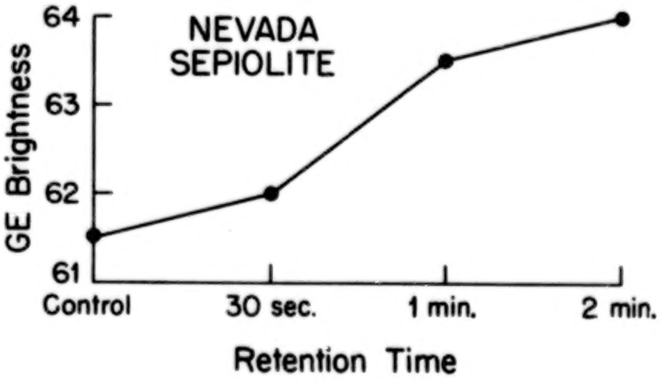


Figure 30 - Brightness of sepiolite vs. retention time.

TALC

Talc is a hydrated magnesium silicate that is used as a filler in paper, paint, plastics, and rubber and as a prime ingredient in cosmetics. Therefore, the color is a primary concern and any iron bearing minerals that can be removed improve the quality of the talc.

Sample locations - Yellowstone, Montana; Willow Creek, Montana;
Ennis, Montana; Dillon, Montana

Test conditions - Particle size - minus 250 mesh

Canister matrix - Steel wool

Retention time - 30 seconds, 1 minute, 2 minutes

Field strength - 20 kilogauss

Percent solids - 20 - Dispersant - sodium hexametaphosphate

TABLE 31 - Fe analyses and brightness of talc HIMS fractions

Sample	Percent Fe	Brightness
Control (talc) - Yellowstone	1.21	78.5
30 second non-mag.	1.16	80.5
1 minute non-mag.	1.05	81.0
2 minute non-mag.	1.03	82.0
Control (talc) - Willow Creek	1.55	75.0
30 second non-mag.	1.39	76.0
1 minute non-mag.	1.38	76.0
2 minute non-mag.	1.38	76.5
Control (talc) - Ennis	0.60	89.0
30 second non-mag.	0.58	91.0
1 minute non-mag.	0.57	91.5
2 minute non-mag.	0.57	92.5
Control (talc) - Dillon	0.97	78.0
30 second non-mag.	0.32	82.0
1 minute non-mag.	0.30	82.5
2 minute non-mag.	0.21	83.5

Discussion - The Montana talc samples all lend themselves to beneficiation using HIMS. The iron percentage is reduced in all the samples and the brightness values increase. The highest quality material is the Ennis talc and the brightness increased from 89 to 92.5, a very significant improvement. The magnetic fraction was very green colored and X-ray diffraction analyses revealed that it was largely chlorite, a hydrated magnesium iron silicate. The results of using HIMS to beneficiate the talcs to improve their brightness is very encouraging and further detailed investigations are recommended.

TRIPOLI

Tripoli is a very fine particle size silica that is used as a filler, extender pigment, and polishing compound. The iron content affects the brightness and if the product brightness could be improved tripoli could be used for more applications.

Sample location - Cairo, Illinois
Test conditions - Particle size - minus 325 mesh
Canister matrix - Steel wool
Retention time - 30 seconds, 1 minute, 2 minutes
Field strength - 20 kilogauss
Percent solids - 20 - Dispersant - sodium hexametaphosphate

TABLE 32 - Fe analyses of tripoli HIMS fractions

Sample	Percent Fe
Control (tripoli) - Illinois	0.030
30 second non-mag.	0.015
1 minute non-mag.	0.013
2 minute non-mag.	0.011

Discussion - The iron content of the tripoli sample was very much reduced and as shown on Figure 31 the brightness was improved from 85.4 to 88.2 which is a very significant improvement in color. HIMS certainly has potential application in the beneficiation of the Illinois tripoli and further evaluation is recommended.

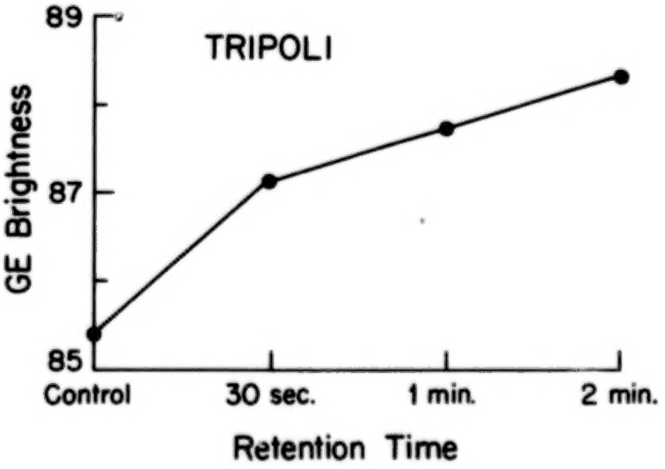


Figure 31 - Brightness of tripoli vs. retention time.

VOLCANIC ASH

Volcanic ash is a glassy granular material which is gray white in color and is used in white cement. Iron minerals reduce the color of the ash and if they can be removed the color should be improved.

Sample location - Gonzales County, Texas
Test conditions - Particle size - minus 100 mesh
Canister matrix - Frantz screens
Retention time - 30 seconds, 1 minute, 2 minutes
Field strength - 20 kilogauss
Percent solids - 20 - Dispersant - sodium hexametaphosphate

TABLE 33 - Fe analyses of volcanic ash HIMS fractions

Sample	Percent Fe
Control (volcanic ash) - Texas	1.03
30 second non-mag.	0.84
1 minute non-mag.	0.77
2 minute non-mag.	0.72

Discussion - The iron content of the volcanic ash was lowered. Figure 32 shows the brightness of the volcanic ash plotted against retention time. Brightness was improved six percentage points which is very visible to the eye. The starting brightness is very low, however, so it is unlikely that HIMS would improve the brightness enough to make it economic to use.

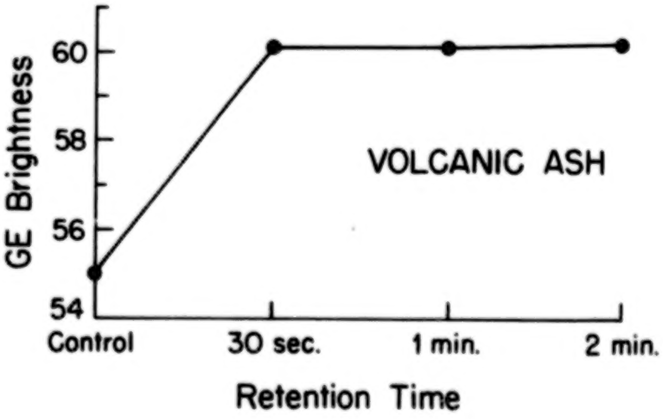


Figure 32 - Brightness of volcanic ash vs. retention time.

WOLLASTONITE

Wollastonite is a calcium silicate that is used in whiteware ceramics such as wall tile as a flux and as a filler in paint, plastics, and other uses. Color and iron content are particularly important in the wall tile application so iron bearing minerals must be removed in order that the tile will fire to a white color. The major iron bearing mineral in the wollastonite is garnet.

Sample location - Willsboro, New York
Test conditions - Particle size - minus 325 mesh
Canister matrix - Steel wool
Retention time - 30 seconds, 1 minute, 2 minutes
Field strength - 20 kilogauss
Percent solids - 20 - Dispersant - sodium hexametaphosphate

TABLE 34 - Fe analyses of wollastonite HIMS fractions

Sample	Percent Fe
Control (wollastonite) - New York	4.15
30 second non-mag.	0.76
1 minute non-mag.	0.54
2 minute non-mag.	0.42

Discussion - The wollastonite sample contained a large amount of iron in the form of garnet. As shown above a very large proportion of the garnet was removed by the HIMS process. Therefore, HIMS has potential application in beneficiating wollastonite and further evaluations should be undertaken.

HIMS OF SELECTED BITUMINOUS COALS

Among the various impurities in coal, sulfur is one of the most prevalent and pervasive, and it has long been a serious problem since it interferes in one way or another with most major uses of coal. In spite of years of research and development only a few desulfurization methods are perfected and used commercially. Those methods in commercial use generally depend on making a simple physical separation of coarse sulfur-bearing mineral particles from coal. Many coal deposits contain finely disseminated minerals and organically combined sulfur which cannot be removed by these methods. Therefore, new and more effective methods for desulfurizing coals must be developed.

One potential method for removing the fine sulfur-bearing minerals and lowering the ash content is high gradient magnetic separation. As previously mentioned the coal is diamagnetic and the pyritic sulfur and many of the minerals which form the ash are paramagnetic. Therefore, the major concern was to liberate these sulfur and ash forming minerals by pulverizing the coal to an optimum size.

In this study the coal samples were pulverized to several sizes including minus 100 mesh, minus 200 mesh, and minus 325 mesh. After pulverizing, the samples were slurried at 30 percent solids and dispersed using sodium hexametaphosphate.

The coals used in the study were commerically mined coals from West Virginia, Indiana, and Illinois. The following Table 35 designates the coal and the location of the sample.

TABLE 35 - Location and name of coal samples.

Coal	Sample Location
Pittsburgh #8 seam	Marshall County, West Virginia
Indiana Coal V	Warrick County, Indiana
Indiana Coal V	Sullivan County, Indiana
Indiana Coal VI	Warrick County, Indiana
Indiana Coal VI	Greene County, Indiana
Indiana Coal VII	Sullivan County, Indiana
Indiana Coal VII	Vermillion County, Indiana
Illinois Coal V	Wabash County, Illinois
Illinois Coal VI	Williamson County, Illinois

The sulfur and ash values of the coals studied in this project are shown in Table 36.

TABLE 36 - Sulfur and ash values of coal samples in percent

Sample	Ash	Total S	Pyritic S	Sulfate S	Organic S
Pittsburgh #8	10.91	4.02	1.63	0.36	2.03
Indiana Coal V (Warrick)	12.82	4.63	2.32	0.12	2.19
Indiana Coal V (Sullivan)	10.46	3.98	1.93	0.07	1.98
Indiana Coal VI (Warrick)	11.44	4.17	2.11	0.09	1.97
Indiana Coal VI (Sullivan)	15.35	2.22	1.15	0.11	0.96
Indiana Coal VII (Sullivan)	6.52	2.17	0.75	0.16	1.26
Indiana Coal VII (Vermillion)	36.05	1.88	0.50	0.42	0.96
Illinois Coal V	9.12	3.59	2.24	0.15	1.20
Illinois Coal VI	8.43	1 98	0.96	0.06	0.96

In order to establish the optimum conditions for running the coal samples, Indiana Coal VI from Warrick County was selected for a series of tests varying the field intensity and the matrix. Figure 33 shows a plot of percent sulfur versus field intensity. The control sample had 4.17 percent total sulfur. At 10 kilogauss field intensity the total sulfur was 3.94 percent, a very small reduction. At 15 kilogauss the total sulfur was 2.51 percent and at 20 kilogauss 2.28 percent. The largest sulfur reduction was between 10 and 15 kilogauss but at 20 kilogauss the sulfur value was the lowest so all runs on the other samples were made at a constant setting of 20 kilogauss.

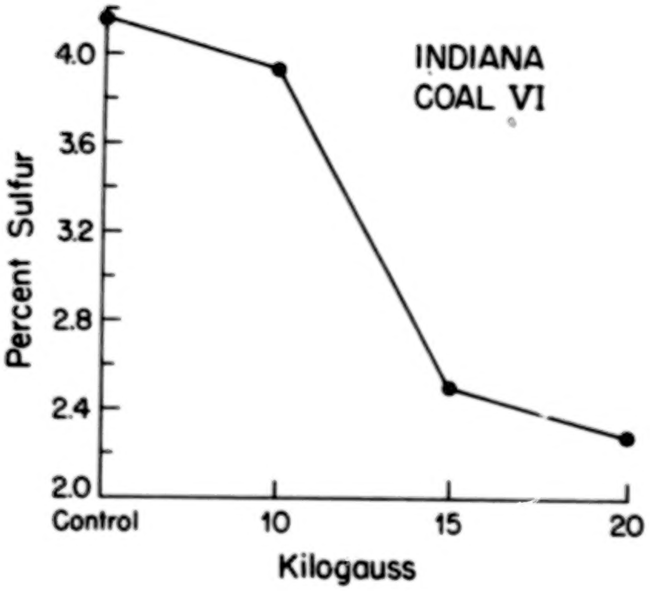


Figure 33 - Percent sulfur vs. field intensity of coal VI.

The fact that the higher field intensity produced the best results was predictable in that most paramagnetic minerals show increasing magnetic susceptibility the higher the field intensity.

Next a series of runs were designed to determine the effectiveness of the matrix material. Table 37 shows the results.

TABLE 37 - Effect of Matrix on Pyrite Removal From Indiana Coal VI

Description	Total Sulfur (%)	Pyritic Sulfur (%)
Control Sample Coal VI	4.17	2.20
Stainless Steel Wool Roving	2.95	0.98
Steel Shavings	2.69	0.72
Frantz Screens	2.45	0.48
Steel Wool Pads (Separator Plugged)		

The coal VI samples were pulverized so that 90% passed through a 200 mesh screen and a constant retention time of 120 seconds was used. The best matrix material for the coal pulverized to this size was the Frantz screens which removed 78.3% of the pyritic sulfur.

The next series of runs were to determine the effect of retention time. The Frantz screens were used as the matrix and the pulverized coal VI (90% through 200 mesh) was used. Figure 34 shows the results. At 30 seconds retention the total sulfur dropped to 3.2%, at 60 seconds to 2.85%, and at 120 seconds to 2.45% which clearly shows that the longer retention time was necessary.

After determining that the longer retention time (120 seconds) removed the highest percentage of pyritic sulfur a comparison was made by running coal VI through the canister four times with 30 seconds retention each. These results are shown in Table 38.

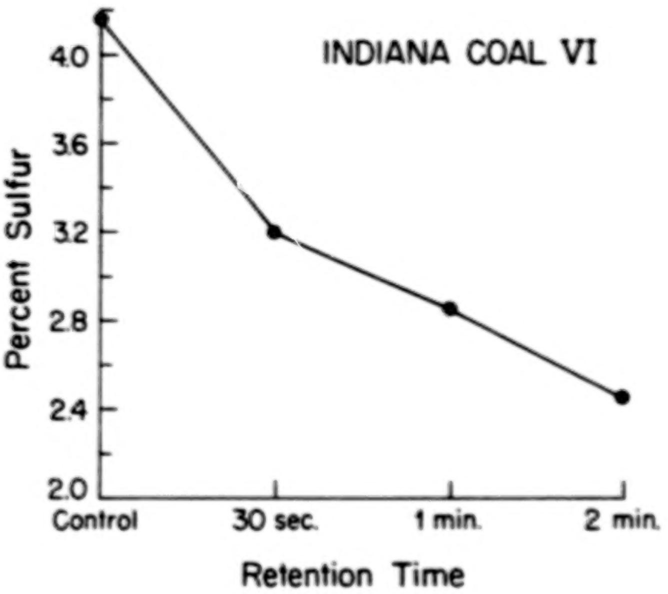


Figure 34 - Percent sulfur vs. retention time of coal VI.

TABLE 38 - Four Passes Through Canister (30 seconds retention each)

	Total Sulfur	Pyritic Sulfur
Control Sample Coal VI	4.17	2.20
1st pass	3.23	1.26
2nd pass	2.54	0.57
3rd pass	2.33	0.33
4th pass	2.19	0.19

This indicates that running the samples through the canister four times at 30 seconds each removes a higher percentage of the pyritic sulfur than one pass at 120 seconds.

The next tests were to determine the effect of pulverizing the sample to 90% through 325 mesh (44 microns) on removal of the pyritic sulfur. Again using the Frantz screens compared with the sample pulverized to 90% through a 200 mesh screen versus a sample pulverized to 90% through a 100 mesh screen. The results are shown in Table 39. All samples were run at 60 seconds retention time.

TABLE 39 - Comparison of Grind Size on Sulfur Removal

	Total Sulfur	Pyritic Sulfur
Control Sample Coal VI	4.17	2.20
90% minus 100 mesh	3.12	1.15
90% minus 200 mesh	2.64	0.67
90% minus 325 mesh	2.11	0.14

These results show that the finer the grind size the more effective is the magnetic separation.

For comparitive purposes two samples of coal VI, one pulverized so that 90% of the particles passed 200 mesh and the second pulverized so that 90% of the particles passed 325 mesh, were run wet with a retention time of 30 seconds and dry by dropping the sample through the canister from the top by gravity with no control over retention time.

Table 40 shows the results.

TABLE 40 - Comparison of Dry Versus Wet Separation (Frantz Screens)

	Total Sulfur	Pyritic Sulfur
Control Sample Coal VI	4.17	2.20
Dry Separation (90% through 20 mesh)	3.73	1.76
Dry Separation (90% through 325 mesh)	3.09	1.12
Wet Separation (90% through 200 mesh)	2.45	0.48
Wet Separation (90% through 325 mesh)	2.22	0.25

The wet separation produced much better results than the dry separation.

Because the canister filled with pads of stainless steel wool plugged, a canister with the bottom half filled with Frantz screens and the top half filled with stainless steel wool pads was tried. This was successful because the Frantz screens removed enough paramagnetic mineral matter so that the tightly packed steel wool pads did not plug. Table 41 gives the results of running 200 mesh and 325 mesh material at 60 seconds retention time.

TABLE 41 - Results Using Canister Filled With 1/2 Frantz Screens
1/2 Steeless Steel Wool Pads

	Total Sulfur	Pyritic Sulfur
Control Sample Coal VI	4.17	2.20
Sample 90% minus 200 mesh	2.31	0.34
Sample 90% minus 325 mesh	2.08	0.11

The results of the 90% minus 325 mesh sample using the canister with 1/2 Frantz screens and 1/2 steel wool pads were the best of any obtained with 95% of the pyritic sulfur removed.

The samples of coal VI run under the various conditions indicated that the best results were obtained using finely pulverized coal, a 2 minute retention time, a 20 kilogauss intensity, and matrix of 1/2 Frantz screens and 1/2 steel wool pads. However, because of practical matters the following parameters were selected because the coal burning power plants pulverize the coal to about 90% less than 200 mesh and the longer retention time uses more power. The samples listed in Table 35 were run using the following standard conditions.

1. 20 kilogauss intensity
2. Retention time - 60 seconds
3. Matrix - Frantz screens
4. Grind size - 90% less than 200 mesh

The results using the above conditions for all the samples are shown in Table 42.

TABLE 42 - Sulfur and ash removal by HIMS.

Sample	Total Sulfu	Pyritic Sulfur	% Ash
Pittsburgh #8 Control	4.02	1.63	10.9
Pittsburgh #8	3.21	1.18	7.2
Indiana Coal V (Warrick) Control	4.63	2.32	12.8
Indiana Coal V (Warrick)	3.10	0.79	6.4
Indiana Coal V (Sullivan Co.) Control	3.98	1.93	10.5
Indiana Coal V (Sullivan Co.)	2.80	0.66	7.9
Indiana Coal VI (Warrick Co.) Control	4.17	2.11	11.4
Indiana Coal VI	2.45	0.48	6.8
Indiana Coal VI (Sullivan Co.) Control	2.22	1.15	15.3
Indiana Coal VI	1.67	0.62	9.9

TABLE 42 (Con't)

Sample	Total Sulfur	Pyritic Sulfur	% Ash
Indiana Coal VII (Sullivan) Control	1.87	1.37	8.94
Indiana Coal VII	1.07	0.16	6.43
Indiana Coal VII (Vermillion Co.) Cont.	2.17	0.75	6.5
Indiana Coal VII	2.07	0.55	6.0
Illinois Coal V - Control	3.59	2.24	10.3
Illinois Coal V	2.18	0.98	6.3
Illinois Coal VI - Control	1.98	0.96	7.1
Illinois Coal VI	1.29	0.33	4.9

The results shown in Table 42 indicate that the results are quite variable depending on the coal, the sulfur content, and the ash content. The best results were obtained on an Indiana coal VII sample from Sullivan County where almost 90 percent of the pyritic sulfur was removed. The worst results were with another sample of Indiana coal VII from Vermillion County where only about 30 percent of the pyritic sulfur was removed. This indicates that each coal must be analyzed individually as far as the distribution of the pyrite, both as to size and dispersion through the coal, in order to best determine the type and size of matrix, the retention time, and the fineness of grind for the coal in order to get maximum liberation and removal of the pyrite. Another distinct advantage of the HIMS method is the significantly lower ash content of the non-magnetic fraction of the coal. All samples yielded a 90 percent or better recovery after being subjected to magnetic separation so the loss of coal is not very high.

In order to determine if the pyritic sulfur was concentrated in a particular size and/or if it is liberated preferentially depending on the grind size, two coals were studied. Indiana coals V and VI were pulverized and screened separating out a minus 100 plus 200 mesh fraction, a minus 200 plus 325 mesh fraction, and a minus 325 mesh fraction. Each of these fractions from both coals were run through the HIMS under the same conditions i.e. 20 kilogauss field strength, 60 second retention time, and a matrix of Frantz screens. The results are shown in Table 43.

TABLE 43 - Sulfur and Ash Values in Percent on Size Fractions of Indiana Coals V and VI

Coal and Mesh		Total Sulfur	Pyritic Sulfur	% Ash
Indiana Coal V	100-200 mesh	3.98	1.93	10.46
Indiana Coal V	200-325 mesh	3.55	1.61	10.08
Indiana Coal V	Minus 325 mesh	3.04	1.34	12.01
Indiana Coal V	100-200 mesh non-mags	2.80	0.66	7.91
Indiana Coal V	200-325 mesh non-mags	2.66	0.67	8.20
Indiana Coal V	Minus 325 mesh non-mags	2.76	0.90	10.83
Indiana Coal VI	100-200 mesh	2.22	1.15	15.35
Indiana Coal VI	200-325 mesh	2.18	1.13	16.47
Indiana Coal VI	Minus 325 mesh	2.13	1.03	20.32
Indiana Coal VI	100-200 mesh non-mags	1.67	0.62	9.95
Indiana Coal VI	200-325 mesh non-mags	1.58	0.60	12.17
Indiana Coal VI	Minus 325 mesh non-mags	1.35	0.67	17.2

The coals for this study were from Sullivan County Indiana. The results showed that the sulfur values are higher in the coarser particles both the total and pyritic. The total sulfur values in the non-magnetic fractions were lowest in the minus 325 mesh fraction but the ash value was highest in this fraction. There was not a dramatic difference in the values comparing the three fractions however.

A sample of coal V was ground to -200 mesh and run first through a Frantz screen matrix at 20 kilogauss and 30 seconds retention time. The non-magnetic fraction was then rerun through the magnet using a steel wool matrix at 20 kilogauss field strength and 30 seconds retention. The results are shown in Table 44.

TABLE 44 - Sulfur and Ash Analyses in Percent of Coal V (Minus 200 mesh) Run Through Frantz Screens and Steel Wool.

	Total Sulfur	Pyritic Sulfur	Ash
Control Sample	3.55	1.61	10.08
Frantz Screens Non-Mags	3.20	0.96	7.95
Steel Wool Non-Mags	2.45	0.42	5.81

These results show that the stainless steel wool matrix is much more efficient in removing the pyritic sulfur from the coal but unless it is ground to minus 325 mesh or is first run through a Frantz screen matrix if the material is minus 200 mesh, the stainless steel matrix will continually plug up.

Coal VII, the Danville coal, is a relatively low sulfur coal in comparison with coals V, the Springfield coal, and Coal VI, the Hymera coal. A sample of a low sulfur coal VII was pulverized so that 90 percent of the coal passed through a 200 mesh sieve. The sample was split and one half was run through the HIMS unit and the other half was run in a froth flotation cell. The sample was run in the cell at 10 percent solids using 4-methyl -2-pentanol as the frother and sodium metaphosphate as the dispersant. The HIMS conditions were 20 kilogauss field strength, 30 percent solids, a 1/2 Frantz screen 1/2 steel wool matrix, and 30 seconds retention time. The results are shown in Table 45.

TABLE 45 - Sulfur and ash values in percent of samples of Coal VII run through HIMS and a flotation cell

	Total Sulfur	Pyritic Sulfur	Ash
Coal VII - Control	1.94	0.69	8.86
Coal VII - Non-Mags	1.51	0.20	6.43
Coal VII - Flotation	1.31	0.49	4.13

The froth flotation removed more pyritic sulfur and ash than the magnetic separator but it is estimated that the froth flotation would be about 2 1/2 times the cost of magnetic separation and the results are not that much different.

It is estimated that a commercial scale magnetic cleaning circuit capable of producing 500 tons of coal per hour would require the use of six 84-inch magnets. The capital cost of an installation of this magnitude would be of the order of $18,000,000. Operating costs including amortization, power, labor, and maintenance would be approximately $1.00 to $1.50 per ton. This cost of removing a major proportion of the pyritic sulfur and ash is very reasonable.

A serious drawback to the HIMS method is that the coal must be slurried in order to get optimum removal of the pyritic sulfur and ash. Coal dewaters readily however so this high intensity magnetic separation technique deserves extensive further evaluation.

HIMS OF SELECTED METALLIC ORES

Magnetic beneficiation and concentration of ore minerals operates on the principle that the mineral or material to be concentrated is a discrete magnetizable component of a system made up of magnetic and non-magnetic parts. The material, ore and gangue is passed through the magnetic force field and the magnetic component is retained and the non-magnetic component passes through the field. The beneficiated product can be either the magnetic or the non-magnetic component depending upon the ore material.

Conventional mineral beneficiation methods become relatively inefficient as the particle size of the material to be processed decreases. One of the most widely used beneficiation and concentration methods is froth flotation. However, difficulty with this process is often encountered at the finer particle sizes, particularly when the particle size gets below 10 microns. The fine particles are lost in the process and are called slimes. In many instances valuable material is discarded in the slimes. HIMS, particularly when the matrix in the canister is fine steel wool, is potentially a beneficiation process which can recover values from slimes if the values are in magnetic or paramagnetic mineral particles. Also, values could be recovered from tailings in slurry ponds.

The HIMS unit can be used alone or in conjunction with flotation, ore phase extraction, selective flocculation, gravity concentration, or other processes. Many deposits that are now classified as marginal or sub-marginal can possibly become reserves if magnetic separation methods are successful in concentrating and upgrading metallic mineral products.

This study is a survey and does not attempt to optimize all parameters on each metallic mineral but rather will indicate that further research and development could lead to commercial utilization of HIMS as a beneficiation process. The metallic mineral ores that were processed through the HIMS unit are as follows.

Chromium
Copper
Iron
Lead
Nickel
Tin
Titanium
Tungsten
Zinc

CHROMIUM

The United States is one of the worlds largest consumers of metallic chromium. All chromite, the commercial ore mineral of chromium, used in the United States is imported from the USSR, Turkey, Republic of South Africa, Philippines, and Rhodesia. The Stillwater complex in Montana is estimated to contain 80 percent of the chromite ore resources of the United States The object of this study of the Montana chromite is to determine if HIMS can be used to upgrade these low grade, high iron, chromite bearing ores sufficiently so that they could be used alone or in conjunction with the high grade foreign ores. Samples were obtained from two areas in the Stillwater complex, Mountain View and Benbow. Mountain View is adjacent to the Stillwater River and Benbow is near Little Rocky Creek.

Chromite is a chemically complex solid solution mineral that consists of variable proportions of five major cations; chromium, aluminum, magnesium, ferrous iron, and ferric iron. The grade of chromite ore is expressed in terms of weight percent Cr_2O_3 and the weight ratio of metallic chromium to total metallic iron. The theoretical composition of true chromite $Fe\ Cr_2O_4$ is 68 percent Cr_2O_3 and 32 percent FeO.

Polished thin sections of the chromite ore were examined in order to determine the mineralogy and texture. Particular attention was given to the type, mode of occurrence, shape, and size of the gangue minerals. X-ray diffraction analyses were also used to identify the minerals and identify the chromium-spinel phases present. For the HIMS study the chromite ore samples were pulverized in a rod mill.

The mineralogy of the chromite ore consists of massive aggregates of chromite grains, serpentine, biotite, bronzite, orthoproxenes, and quartz. The samples were rod milled to minus 100, minus 200, and minus 325 mesh sizes to determine the best size for HIMS. The field intensity was varied using 5, 10, 15, and 20 settings to determine which field intensity gave the best results. The canister was filled with steel wool, Frantz screens, and a special non-blinding matrix provided by Dr. Joe Iannicelli which is as yet proprietary.

The first tests were to determine the best setting for the field intensity in combination with the matrix. It was found that the stainless steel wool matrix had too great a captive force and immediate clogging occurred with all three particle sizes of the chromite. Therefore, the stainless steel wool matrix was eliminated as a viable alternative.

The next tests were to compare the Frantz screen matrix with the non-blinding matrix. A chromite sample from Benbow using a particle size of minus 200 mesh, 10 percent solids slurry, 30 seconds retention time, and a 20 kilogauss magnetic field strength was used for the comparative test. The results are shown on Table 46.

TABLE 46 - Iron and chrome analyses using Frantz screens compared with the non-blinding matrix

Sample	Weight Percent	Fe	Cr_2O_3	Cr: Fe ratio
Control - Benbow		13.5	31.86	1: 1.50
Non-blinding matrix non-mags.	91.6	12.7	30.98	1: 1.20
Non-blinding matrix mags.	8.4	17.7	33.62	1: 1.53
Frantz screens non-mags.	18.8	10.3	26.02	1: 1.60
Frantz screens mags.	81.2	13.7	33.82	1: 1.18

The major difference between the two matrices is the percentage by weight of the non-mags versus the mags recovered. The non-blinding matrix yielded 90 plus percent by weight non-mags while the Frantz screen matrix yielded approximately 19 percent. The total iron was slightly reduced in the non-mag fractions and the chromium percentage was slightly increased in the mag fraction. However, these results indicate very little beneficiation of the chrome content.

Because the magnetic susceptibility is relatively high (29), the next series of test were to adjust the magnetic intensity using kilogauss field strengths of 20, 15, 10, and 5. A retention time of 30 seconds was used and the grind sizes of the chromite were minus 100, minus 200, and minus 325. The results are shown in Table 47.

TABLE 47 - Iron and chrome analyses of Benbow #1 chrome ore, comparing the non-blinding matrix to the Frantz screens matrix with a 30 second retention time and varying particle size and magnetic intensity

Sample	Magnetic Intensity	Particle Size	Wt. %	Fe, total	Cr_2O_3	Cr:Fe
Control, Benbow #1				13.5%	31.86%	1:1.50
Non-mags, FS, 0.5 min.	20 KG	-100	14.36%	7.6%	13.15%	1:1.69
Mags, FS, 0.5 min.	20 KG	-100	85.64%	13.5%	32.74%	1:1.21
Non-mags, NB, 0.5 min.	20 KG	-100	97.1%	12.4%	26.89%	1:1.35
Mags, NB, 0.5 min.	20 KG	-100	2.9%		No analysis	
Non-mags, FS, 0.5 min.	15 KG	-100	16.15%	7.2%	11.4%	1:1.85
Mags, FS, 0.5 min.	15 KG	-100	83.85%	13.3%	32.15%	1:1.21
Non-mags, NB, 0.5 min.	15 KG	-100		No run made		
Mags, NB, 0.5 min.	15 KG	-100				
Non-mags, FS, 0.5 min.	10 KG	-100	19.71%	7.5%	12.72%	1:1.72
Mags, FS, 0.5 min.	10 KG	-100	80.29%	13.2%	30.11%	1:1.28
Non-mags, NB, 0.5 min.	10 KG	-100	98.4%	12.5%	30.11%	1:1.21
Mags, NB, 0.5 min.	10 KG	-100	1.6%		No analysis	
Non-mags, FS, 0.5 min.	5 KG	-100	19.15%	8.5%	14.76%	1:1.68
Mags, FS, 0.5 min.	5 KG	-100	80.85%	13.2%	33.18%	1:1.16
Non-mags, NB, 0.5 min.	5 KG	-100	98.9%	10.8%	28.35%	1:1.11
Mags, NB, 0.5 min.	5 KG	-100	1.1%		No analysis	

FS = Frantz screen
NB = Non-blinding matrix
min. = Retention time
KG = Kilogauss

TABLE 47 (continued)

Sample	Magnetic Intensity	Particle Size	Wt. %	Fe, total	Cr_2O_3	Cr:Fe
Control, Benbow #1				13.5%	31.86%	1:1.50
Non-mags, FS, 0.5 min.	15 KG	-200	19.28%	9.1%	20.90%	1:1.27
Mags, FS, 0.5 min.	15 KG	-200	80.72%	14.6%	34.78%	1:1.23
Non-mags, NB, 0.5 min.	15 KG	-200		No run made		
Mags, NB, 0.5 min.	15 KG	-200				
Non-mags, FS, 0.5 min.	10 KG	-200	20.3%	9.0%	20.46%	1:1.29
Mags, FS, 0.5 min.	10 KG	-200	79.7%	13.7%	32.45%	1:1.23
Non-mags, NB, 0.5 min.	10 KG	-200	95.3%	12.5%	30.98	1:1.18
Mags, NB, 0.5 min.	10 KG	-200	4.7%		No analysis	
Non-mags, FS, 0.5 min.	5 KG	-200	24.25%	10.0%	20.90%	1:1.40
Mags, FS, 0.5 min.	5 KG	-200	75.75%	14.9%	34.05%	1:1.28
Non-mags, NB, 0.5 min.	5 KG	-200	98.9%	12.3%	29.23%	1:1.23
Mags, NB, 0.5 min.	5 KG	-200	1.1%		No analysis	

FS = Frantz screen
NB = Non-blinding matrix
min. = Retention time
KG = Kilogauss

TABLE 47 (continued)

Sample	Magnetic Intensity	Particle Size	Wt. %	Fe, total	Cr_2O_3	Cr:Fe
Control, Benbow #1				13.5%	31.86%	1:1.50
Non-mags, FS, 0.5 min.	20 KG	-325	8.20%	7.7%	15.64%	1:1.44
Mags, FS, 0.5 min.	20 KG	-325	91.80%	14.0%	27.77%	1:1.47(?)
Non-mags, NB, 0.5 min.	20 KG	-325	96.6%	12.2%	22.80%	1:1.56
Mags, NB, 0.5 min.	20 KG	-325	3.4%		No analysis	
Non-mags, FS, 0.5 min.	15 KG	-325	15.15%	10.0%	20.61%	1:1.42
Mags, FS, 0.5 min.	15 KG	-325	84.85%	14.3%	31.42%	1:1.33
Non-mags, NB, 0.5 min.	15 KG	-325		No run made		
Mags, NB, 0.5 min.	15 KG	-325				
Non-mags, FS, 0.5 min.	10 KG	-325	17.35%	9.0%	17.90%	1:1.47
Mags, FS, 0.5 min.	10 KG	-325	82.65%	14.0%	32.15%	1:1.27
Non-mags, NB, 0.5 min.	10 KG	-325	95.8%	11.5%	21.92%	1:1.53
Mags, NB, 0.5 min.	10 KG	-325	4.2%		No analysis	
Non-mags, FS, 0.5 min.	5 KG	-325	21.80%	10.0%	20.61%	1:1.42
Mags, FS, 0.5 min.	5 KG	-325	78.20%	14.8%	32.45%	1:1.33
Non-mags, NB, 0.5 min.	5 KG	-325	97.8%	11.0%	24.85%	1:1.29
Mags, NB, 0.5 min.	5 KG	-325	2.2%		No analysis	

FS = Frantz screen
NB = Non-blinding matrix
min. = Retention time
KG = Kilogauss

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Again the results show that the major difference between runs made using Frantz screens and the non-blinding matrix is the weight percentage of non-mags versus mags. In a majority of runs, the weight ratio of metallic chromite to total metallic iron is reduced using the non-blinding matrix. The Frantz screen non-mags consistently produced higher percentages of Cr_2O_3 as compared to the non-blinding matrix mags. Again because of the fairly high magnetic susceptibility of chromite the thirty second retention time was used. Shorter retention times would have been tested but the available pump only had a maximum flow rate of 1400 cc per minute or the equivalent of a 27 second retention time.

Comparing the results on the basis of grind size shows that the most effective iron removal was achieved using the coarser (minus 100 mesh) size. The differences between the minus 100 mesh and the minus 200 mesh sizes are so slight as to be negligible. For the sake of convenience in the chemical analyses the minus 200 mesh size was used.

The results of these HIMS tests on chromite indicate that this process could not be considered as a commercially feasible process for beneficiating the chromite ore from the Stillwater complex in Montana. Follow up research could be done on a canister consisting of alternating Frantz screens and non-blinding matrix material. Also, runs should be made with retention times of 15 seconds or shorter in order to overcome the high magnetic susceptibility of chromite.

COPPER

The purpose of this study was to determine if copper was enriched in magnetic fraction of flotation feed materials. Samples were obtained from Magma, Arizona; Butte, Montana; and Sahuarita, Arizona. Samples were run at 30 seconds retention time using 10 and 20 kilogauss field intensity and matrices of steel wool and Frantz screens. These are sulfide ores and the particle size is minus 200 mesh. The results are shown in Table 48.

Table 48 - Copper analyses in percent

Sample	Cu
Control - Butte, Montana #1	2.13
10 KG SW	3.07
10 KG FS	2.66
20 KG SW	2.94
20 KG FS	2.56
Control - Butte, Montana #2	1.60
10 KG SW	1.52
10 KG FS	1.64
20 KG SW	1.76
20 KG FS	1.68
Control - Magma, Arizona	0.21
10 KG SW	0.32
10 KG FS	0.28
20 KG SW	0.29
20 KG FS	0.33
Control - Sahuarita, Arizona	1.22
10 KG SW	1.62
10 KG FS	1.38
20 KG SW	1.55
20 KG FS	1.37
Control - Sahuarita, Arizona	1.06
10 KG SW	1.20
10 KG FS	1.40
20 KG SW	1.17
20 KG FS	1.04

KG = Kilogauss; SW = Steel Wool; FS = Frantz Screen

The results indicate that there is an increase of copper in the magnetic fraction but not enough to justify the use of HIMS as a concentration process. Additional work should be done relating matrix composition, particle size, and magnetic field strength because in every case the copper percentage was increased in the magnetic fraction. There were mixed results between the 10 KG intensity and 20 KG intensity so that no conclusion could be drawn concerning field strength. The steel wool canister was a more effective matrix to concentrate the copper.

ILMENITE

A sample of ilmenite ore from New York state was ground in the rod mill to minus 200 mesh and run through the HIMS at 20 KG field strength using Frantz screens and 10% solids. The results are shown in Table 49.

TABLE 49 - Fe and TiO_2 analyses of ilmenite HIMS fractions.

	WT %	% Fe	% TiO_2
Feed	100	22.4	19.1
Mag	56	43.18	37.48
Non-mag	44	7.62	4.83

The results indicate that ilmenite can be concentrated using the HIMS and further studies should be conducted.

TACONITE IRON ORE

The Lake Superior region of Michigan, Wisconsin, and Minnesota contains the bulk of the iron resources of the United States. A large proportion of these resources is taconite, a silica rich magnetite rock. When the taconite is oxidized the iron minerals are quartz, hematite, and goethite which are unsuitable for conventional magnetic separation techniques. The development of a process for the economic beneficiation of oxidized taconite would convert 10 billion metric tons from a resource status to iron reserves.

HIMS is only one of a number of beneficiation techniques which have potential application to oxidized taconties. Treatment of these oxidized taconites to beneficiate them to higher iron values is the best way to expand domestic iron production at a cost that is near current levels (30). There has been much interest in high intensity separation as a means of concentrating weakly magnetic minerals. Important research on the magnetic beneficiation of oxidized taconite has been done at the University of Minnesota Mines Experiment Station (31), the U.S. Bureau of Mines Twin Cities Metallurgy Research Center in Minneapolis-St. Paul, Minnesota (30, 32), MIT Francis Bitter Magnet Laboratory (33), and the Hanna Mining Company Research Laboratory in Nashwauk, Minnesota.

The samples used in this study came from the Butler Mine near Nashwauk, Minnesota, the Tilden Mine near Ishpeming, Michigan, and a sample representative of the oxidized taconite of the western Mesabi district from the U.S. Bureau of Mines Twin Cities Research Center. The samples from the Butler Mine came from the Biwabik formation and represent the lower cherty and upper cherty members. The samples from the Tilden Mine represent the Negaunee iron formation.

The samples were ground in a laboratory rod mill 9 inches in length and 7 inches in diameter. The mill contained 26 stainless steel rods weighing 500 grams each and turned at 90 RPM. The iron ore slurry was ground in the rod mill at 60 percent solids. The size of the particles were 100 percent finer than 325 mesh.

The first set of tests were performed on the hematite and goethite ores from the Tilden Mine because of the purity of the iron bearing minerals in this oxidized ore. Field strength, retention time, direction of flow through the canister (upflow vs. downflow), and grinding time in the rod mill were examined. All tests were performed with a matrix of Frantz screens. The results are shown in Table 50.

TABLE 50 - Results on Taconite from Tilden Mine

Experiment A - Field: 2.5 KG Goethite Ore, 29.1% Fe, 1.5 hr grind
Matrix: 10" Frantz Screens; Upward Flow

Retention Time		Mag	Non-mag	Flush-mag
1) 30 seconds	Weight	27.4	26.8	47.6
	% Fe	31.0	25.0	30.5
	% Recovery	28.5	22.7	49.1
2) 15 seconds	Weight	14.3	51.0	41.2
	% Fe	33.0	25.0	34.5
	% Recovery	15.1	41.2	45.7

Experiment B - Field: 10 KG Goethite Ore, 29.1% Fe, 1.5 hr grind
Matrix: 10" Frantz Screens; Upward Flow

Retention Time		Mag	Non-mag	Flush-mag
1) 30 seconds	Weight	38.8	24.1	44.5
	% Fe	30.0	23.0	30.5
	% Recovery	37.1	17.5	43.3
2) 15 seconds	Weight	22.9	49.5	42.1
	% Fe	33.0	24.0	34.0
	% Recovery	22.7	35.7	42.9

Experiment C - Field: 2.5 KG Hematite Ore, 36.0% Fe, 1.5 hr grind
Matrix: 10" Frantz Screens; Upward Flow

Retention Time		Mag	Non-mag	Flush-mag
1) 30 seconds	Weight	70.4	13.4	39.8
	% Fe	36.0	24.5	32.5
	% Recovery	56.9	7.5	29.2
2) 15 seconds	Weight	51.2	18.9	36.0
	% Fe	37.0	23.0	38.0
	% Recovery	49.7	11.4	35.8

Experiment D - Field: 10KG Hematite Ore, 36.0% Fe, 1.5 hr grind
Matrix: 10" Frantz Screens; Upward Flow

Retention Time		Mag	Non-mag	Flush-mag
1) 30 seconds	Weight	56.5	16.9	31.9
	% Fe	38.5	22.0	36.5
	% Recovery	57.2	9.7	30.8
2) 15 seconds	Weight	73.6	13.6	42.5
	% Fe	37.0	23.0	34.0
	% Recovery	58.3	6.7	30.8

TABLE 50

Experiment E - Field: 2.5 KG, Hematite Ore, 36.0% Fe, 1.5 hr grind

Matrix: 10" Franz Screens; Downward Flow

Retention Time		Mag	Non-mag	Flush-mag
1) 30 seconds	Weight	45.2	64.7	0.7
	% Fe	48.0	24.5	45.5
	% Recovery	54.4	39.7	0.8
2) 15 seconds	Weight	55.7	69.3	2.5
	% Fe	47.0	24.5	45.5
	% Recovery	56.9	36.9	2.5

Experiment F - Field: 2.5 KG Hematite Ore, 36.0% Fe, 1.5 hr grind

Matrix: 10" Frantz Screens; 30 sec retention; 0.6 g dispersant/liter

Direction of Flow		Mag	Non-mag	Flush-mag
1) Downward flow	Weight	58.4	88.6	2.6
	% Fe	56.5	23.5	56.0
	% Recovery	61.3	38.7	2.7
2) Upward flow	Weight	87.8	39.4	19.9
	% Fe	41.5	17.0	57.0
	% Recovery	68.8	12.6	21.4

Experiment G - Field: 10 KG Hematite Ore, 36.0% Fe, 4 hr grind

Matrix: 10" Franz Screens; Upward Flow; 0.6 g dispersant/liter

Retention Time		Mag	Non-mag	Flush-mag
1) 30 seconds	Weight	78.1	30.3	17.5
	% Fe	39.5	11.5	54.0
	% Recovery	68.1	7.7	20.8

Experiment H - Field: 10 KG Goethite Ore, 29.1% Fe, 4 hr grind

Matrix: 10" Frantz Screens; Downward Flow; 0.6 g dispersant/liter

Retention Time		Mag	Non-mag	Flush-mag
1) 30 seconds	Weight	30.8	92.0	4.8
	% Fe	41.5	22.5	41.5
	% Recovery	34.4	55.7	5.5
2) 15 seconds	Weight	44.0	100.5	2.2
	% Fe	42.5	23.5	43.5
	% Recovery	43.6	55.3	2.4

Increased field strength produced higher recovery in all tests and higher grades in some tests. The use of dispersant increased grade and recovery in both upflow and downflow tests. Downward flow produces concentrates with higher grades and lower recoveries than upward flow. The amount of non-magnetic fraction is increased by downward flow. The grinding time did not produce a large change in the results so only two test results were included in Table 50.

A second series of tests were designed to produce an economic grade of concentrate after a single pass through the magnet. The canister used was filled with a special non-blinding matrix that is proprietary and was supplied by Dr. Joe Iannicelli of Aquafine Corporation. All the tests were run at 10% solids, downflow, dispersed with 0.1 g. of tetrasodium pyrophosphate per 100 grams of solids. The test results are shown in Table 51. The samples used were hematite and goethite ores from the Tilden Mine in the Marquette district of Michigan using varying flow velocities and grinding times. There was essentially no flush magnet fraction from this special non-blinding matrix.

TABLE 51 - Test Results on Oxidized Taconites from the Tilden Mine Using the Special Non-blinding Matrix

Test Series 1 - Field: 20 KG Hematite Ore, 36% Fe, 1.5 hr grind

Retention Time		Non-mag	Mag
A) 30 seconds	Weight (gm)	119	14.3
	% Fe	30.5	64.0
	% Fe Recovery	75.5	19.2
B) 15 seconds	Weight	122.2	14.6
	% Fe	33.5	63.5
	% Fe Recovery	83.1	18.9
C) 7.5 seconds	Weight	119.0	12.3
	% Fe	34.0	64.0
	Fe Recovery	85.5	16.6

Test Series 2 - Field: 10 KG Hematite Ore, 36% Fe, 1.5 hr grind

Retention Time		Non-mag	Mag
A) 30 seconds	Weight	118.9	10.6
	% Fe	31.0	64.0
	Fe Recovery	78.9	14.4
B) 15 seconds	Weight	127.2	10.6
	% Fe	33.5	61.5
	Recovery	85.8	13.1
C) 7.5 seconds	Weight	128.4	8.2
	% Fe	31.0	63.5
	Recovery	80.8	10.6

Test Series 3 - Field: 5 KG Hematite Ore, 36% Fe, 1.5 hr grind

Retention Time		Non-mag	Mag
A) 30 seconds	Weight (gr)	127.1	7.9
	% Fe	33.5	62.5
	Recovery	87.5	10.3
B) 15 seconds	Weight	124.0	7.3
	% Fe	32.5	62.5
	Recovery	85.3	9.7
C) 7.5 seconds	Weight	118.5	5.5
	% Fe	33.0	63.5
	Recovery	87.6	7.8

TABLE 51

Test Series 4 - Field: 20 KG Hematite Ore, 36% Fe, 20 minute grind

Retention Time		Non-mag	Mag
A) 30 seconds	Weight	104.5	15.3
	% Fe	32.0	61.5
	Recovery	77.4	21.8
B) 15 seconds	Weight	100.9	13.3
	% Fe	31.5	62.5
	Recovery	77.1	20.1
C) 7.5 seconds	Weight	111.6	9.3
	% Fe	33.0	64.5
	Recovery	84.6	13.8

Test Series 5 - Field: 5 KG Hematite Ore, 36% Fe, 20 minute grind

Retention Time		Non-mag	Mag
A) 30 seconds	Weight	128.6	8.3
	% Fe	34.0	62.0
	Recovery	88.7	10.4
B) 15 seconds	Weight	106.5	5.6
	% Fe	31.5	63.0
	Recovery	83.1	8.7
C) 7.5 seconds	Weight	128.1	5.4
	% Fe	32.5	64.0
	Recovery	86.6	7.2

Test Series 6 - Field: 10 KG Goethite Ore, 29.5% Fe, 1.5 hr grind

Retention Time		Non-mag	Mag
A) 30 seconds	Weight	133.5	3.7
	% Fe	28.5	49.5
	Recovery	94.0	4.5
B) 15 seconds	Weight	130.3	2.7
	% Fe	29.0	50.5
	Recovery	96.3	3.5
C) 7.5 seconds	Weight	134.7	2.0
	% Fe	27.0	54.0
	Recovery	90.2	2.7

TABLE 51

Test Series 7 - Field: 5 KG Goethite Ore, 29.5% Fe, 1.5 hr grind

Retention Time		Non-mag	Mag
A) 30 seconds	Weight	144.6	2.6
	% Fe	27.0	44.0
	Recovery	90.0	2.6
B) 15 seconds	Weight	134.7	2.5
	% Fe	27.0	49.0
	Recovery	90.0	3.0
C) 7.5 seconds	Weight	134.6	1.7
	% Fe	28.0	53.5
	Recovery	93.7	2.3

Test Series 8 - Field: 20 KG Goethite Ore, 29.5% Fe, 1.5 hr grind

Retention Time		Non-mag	Mag
A) 30 seconds	Weight	124.1	4.7
	% Fe	26.0	53.0
	Recovery	84.9	6.6
B) 15 seconds	Weight	133.5	3.8
	% Fe	26.5	53.5
	Recovery	87.3	5.0
C) 7.5 seconds	Weight	144.6	2.6
	% Fe	29.0	54.5
	Recovery	96.6	3.3

Test Series 9 - Field: 10 KG Hematite Ore, 36% Fe, 20 minute grind

Retention Time		Middlings	Mag
Recycle Mag	Weight	2.3	2.3
	% Fe	59.0	64.0
	Recovery	4.6	5.0
Recycle Non-mag	Weight	1.7	75.6
	% Fe	60.0	31.5
	Recovery	3.6	80.4

TABLE 51

Test Series 10 - Field: 20 KG Goethite Ore, 29.5% Fe, 20 minute grind

Retention Time		Non-mag	Mag
A) 30 seconds	Weight	102.2	4.4
	% Fe	26.0	52.0
	Recovery	84.5	7.2
B) 15 seconds	Weight	110.2	2.1
	% Fe	27.0	53.0
	Recovery	89.8	3.4
C) 7.5 seconds	Weight	114.9	2.6
	% Fe	28.0	56.0
	Recovery	92.8	4.2

Test Series 11 - Field: 10 KG Goethite Ore, 29.5% Fe, 20 minute grind

Retention Time		Non-mag	Mag
A) 30 seconds	Weight	116.7	1.0
	% Fe	27.0	52.5
	Recovery	90.7	1.5
B) 15 seconds	Weight	122.1	2.1
	% Fe	27.2	54.5
	Recovery	90.6	3.1
C) 7.5 seconds	Weight	116.6	1.7
	% Fe	27.5	53.5
	Recovery	91.9	2.6

Test Series 12 - Field: 10 KG Goethite Ore, 29.5% Fe, 20 minute grind

Retention Time		Middlings	Mag
Recycle Mag	Weight	0.7	0.6
	% Fe	44.0	55.0
	Recovery	0.8	1.0
Recycle Non-mag	Weight	0.8	108.2
	% Fe	45.5	25.5
	Recovery	1.1	84.8

The most significant result of this series of tests shown in Table 51 is that an economic grade of concentrate was produced from the hematite ore after a single pass through the magnet. The recovery, however, was very low ranging from 7 to 19 percent. Slightly higher recoveries were achieved (22%) at the expense of a slight decrease in grade. Increased field strength always resulted in increased recovery. Increased retention time resulted in increased recovery but sometimes at the expense of grade. Test series 9 and 12 show the results of some significant tests. Samples were first processed through the magnet in the normal fashion and then the respective fractions were recycled through the magnet with the objective of removing a second high grade concentrate from the non-magnetic fraction, thus improving the grade of the concentrate. If high grade hematite could continue to be removed from the non-magnetic fraction, recovery might be increased to acceptable levels. However, the results of the second pass with the non-magnetic fraction were considerably worse than the first pass. Similar results were found with the goethite ore; recycling the magnetic fraction improved the grade of concentrate but at a considerable loss of recovery.

The third set of tests were designed to determine if magnetic beneficiation could be used to produce a preconcentrate for further processing (Table 52). The results from the first series of tests demonstrated that downflow resulted in a greater reduction in the weight of the sample. To offset the tendency of the downflow operation to produce a concentrate with lower recovery, a combination matrix of 10 inches of Frantz screens and 10 inches of compressed coarse steel wool was used. The Frantz screens were placed in the upper half of the canister and the steel wool in the bottom half. The Frantz screens were to collect the most magnetic particles and the steel wool was intended to collect the less magnetic particles. This also might avoid matrix plugging. All samples were ground 10 minutes and 20 minutes and screened through a 100 mesh sieve. All tests were run with a 24 second retention time which is equivalent to a flow velocity of 2.1 cm/second. It was found that a grinding time of 10 minutes produced better results so it was used on all tests.

Processing the various ores to produce a preconcentrate very effectively reduced the total sample weight which would lower the cost of subsequent processing operations. Recovery in the preconcentrate was generally good ranging from 81 to 95 percent at 20 KG. Lower field strengths produced lower recoveries.

SUMMARY

1. A commercial grade of concentrate can be produced from hematite ore after a single pass but at levels of recovery too low to be economic.

2. Goethite concentrates using HIMS is very marginal.

3. Matrix selectivity is an important parameter. Highly selective matrices will tend to improve grade and decrease clogging but the recovery suffers.

4. Preconcentrates can readily be produced.

TABLE 52 - Preconcentrate Tests

Test 1 - Butler Mine - 30.7% Fe

		Mag	Non-mag
5 KG	Weight %	51.0	49.0
	Weight	47.8	46.0
	% Fe	53.5	10.5
	% Recovery	88.8	16.8
10 KG	Weight %	54.8	45.2
	Weight	52.3	43.2
	% Fe	51.5	5.0
	% Recovery	91.9	7.4
20 KG	Weight %	57.2	42.8
	Weight	61.5	46.0
	% Fe	51.0	5.0
	% Recovery	95.0	6.9

Total weight 296.8   Loss: 1.1%

Test 2 - Butler Mine - 30.7% Fe

		Mag	Non-mag
5 KG	Weight %	51.0	49.0
	Weight	49.2	47.3
	% Fe	51.0	10.0
	% Recovery	84.7	16.0
10 KG	Weight %	54.2	45.8
	Weight	52.2	44.1
	% Fe	50.5	9.0
	% Recovery	89.2	13.4
20 KG	Weight %	57.1	42.9
	Weight	57.0	42.9
	% Fe	51.5	7.5
	% Recovery	95.7	10.5

Total weight 292.7   Loss: 2.4%

TABLE 52

Test 3 - Butler Mine - 37.4% Fe

		Mag	Non-mag
5 KG	Weight %	36.4	63.6
	Weight	31.1	54.3
	% Fe	51.0	31.0
	% Recovery	49.6	52.7
10 KG	Weight %	56.1	43.8
	Weight	54.5	42.5
	% Fe	50.0	24.5
	% Recovery	75.1	28.7
20 KG	Weight %	68.8	31.2
	Weight	78.0	35.4
	% Fe	48.5	15.0
	% Recovery	89.2	12.5

Total weight 295.8 Loss 1.4%

Test 4 - Butler Mine - 37.7% Fe, 24 second retention, mixed matrix

		Mag	Non-mag
5 KG	Weight %	47.0	53.0
	Weight	47.4	53.5
	% Fe	54.0	16.0
	% Recovery	67.3	22.5
10 KG	Weight %	54.6	45.4
	Weight	48.2	40.0
	% Fe	52.5	15.0
	% Recovery	76.1	18.0
20 KG	Weight %	59.1	40.9
	Weight	62.8	43.5
	% Fe	52.0	11.0
	% Recovery	81.5	11.9

Total weight 294.4 Loss 1.5%

TABLE 52

Test 5 - Bureau of Mines - 32% Fe

		Mag	Non-mag
5 K G	Weight %	46.8	53.2
	Weight	35.5	40.3
	% Fe	51.0	11.5
	% Recovery	74.6	19.1
10 KG	Weight %	52.4	47.6
	Weight	42.1	38.2
	% Fe	53.5	8.5
	% Recovery	87.5	12.5
20 KG	Weight %	55.6	44.4
	Weight	77.4	61.9
	% Fe	50.0	4.5
	% Recovery	86.9	6.3

Total weight 295.4 Loss: 1.5%

LEAD

Samples of lead ore, galena, were run on the HIMS unit to see if the lead percentage was enriched in the magnetic fraction. The feed materials were a flotation feed concentrate from Butte, Montana, and Magma, Arizona. The samples were run at 10 and 20 kilogauss intensity through a matrix of steel wool and Frantz screens, and the particles were all minus 200 mesh. The results are shown in Table 53.

TABLE 53 - Lead Analyses in Percent

Sample and Conditions	Pb
Butte, Montana Control	3.41
Butte, Montana 10 KG FS	3.37
Butte, Montana 10 KG SW	3.53
Butte, Montana 20 KG FS	3.23
Butte, Montana 20 KG SW	3.42
Magma, Arizona Control	1.89
Magma, Arizona 10 KG FS	1.83
Magma, Arizona 10 KG SW	1.96
Magma, Arizona 20 KG FS	1.88
Magma, Arizona 20 KG SW	1.92

KG = Kilogauss, SW = Steel Wool, FS = Frantz Screens

The results indicate that HIMS does not concentrate galena in the magnetic fraction.

SILVER AND ZINC

Samples of flotation feed concentrate from Magma, Arizona; Butte, Montana; and Sahuarita, Arizona, contained silver values. The magnetic fraction after passing the ore through the HIMS was analyzed to see if silver was concentrated. The results are shown in Table 54.

TABLE 54 - Silver Analyses in PPM and Zinc in Percent

Sample	Silver Values	Zn Values
#1 Butte, Montana Control	44	2.99
Butte, Montana 10 KG SW	176	3.13
Butte, Montana 10 KG FS	136	2.56
Butte, Montana 20 KG SW	157	3.14
Butte, Montana 20 KG FS	124	2.62
#2 Butte, Montana Control	106	30.0
Butte, Montana 10 KG SW	124	29.0
Butte, Montana 10 KG FS	347	29.3
Butte, Montana 20 KG SW	149	29.5
Butte, Montana 20 KG FS	107	29.5
Magma, Arizona Control	258	0.49
Magma, Arizona 10 KG SW	380	3.13
Magma, Arizona 10 KG FS	192	0.35
Magma, Arizona 20 KG SW	538	0.79
Magma, Arizona 20 KG FS	182	0.80
#1 Sahuarita, Az. Control	53	1.19
Sahuarita, Az. 10 KG SW	40	1.56
Sahuarita, Az. 10 KG FS	66	0.92
Sahuarita, Az. 20 KG SW	66	1.20
Sahuarita, Az. 20 KG FS	116	1.18
#2 Sahuarita, Az. Control	31	1.4
Sahuarita, Az. 10 KG SW	48	1.6
Sahuarita, Az. 10 KG FS	74	1.1
Sahuarita, Az. 20 KG SW	83	1.9
Sahuarita, Az. 20 KG FS	141	1.7

KG = Kilogauss, SW = Steel Wool, FS = Frantz Screens

The samples were all minus 200 mesh. The results show that silver is concentrated in the magnetic fraction and zinc seems to be somewhat enriched although erratic.

TUNGSTEN

A sample of tungsten ore (wolframite) from California was ground in the rod mill to minus 200 mesh and run through the HIMS at a 20 KG setting using Frantz screens. The results are shown in Table 55.

TABLE 55 - Tungsten (WO_3) Analyses in Percent

	WO_3%	WT.%
Feed	3.8	100
Mag	72.5	4
Non-Mag	1.95	96

The results indicate that tungsten (wolframite) is concentrated in the magnetic fraction and the HIMS process merits further study as a beneficiation method for concentrating wolframite.

SUMMARY AND CONCLUSIONS

HIMS has considerable potential as a beneficiation process in the minerals industry (34, 35, 36). The processing costs are reasonable and for a number of applications the results were very encouraging. HIMS is a proven beneficiation process for the kaolin industry and is being used by most of the major kaolin producers in the United States and in England and Western Europe. Certain industrial minerals merit further investigation because the data accumulated as a result of this study indicates that the following industrial minerals were upgraded as a result of HIMS.

Asbestos
Ball clay
Bauxite
Bentonite
Calcite
Diatomaceous earth
Glass sand
Hectorite
Kaolin
Kyanite
Magnesite
Nepheline syenite
Novaculite
Talc
Tripoli
Wollastonite

The use of HIMS can remove iron and titanium bearing minerals which are deleterious to color both in pigments and in ceramic raw materials and to refractory raw material because iron lowers the melting temperature. Another important aspect is that the use of HIMS can upgrade marginal and submarginal deposits to economic reserves. It is estimated that the kaolin reserves in Georgia have about doubled because of the use of HIMS.

The use of HIMS to remove pyritic sulfur from coal looks as if it could be a viable process in the future. Approximately 75 percent or more of the inorganic sulfur in the coals studied could be removed by the HIMS process. A major disadvantage is that the coal must be finely pulverized and put into a slurry in order to remove the pyrite. Future developments, however, may improve HIMS dry separation techniques so that the coal could be processed dry to remove a high percentage of the pyrite. The Electric Power Research Institute sponsored a project at Indiana University to compare HIMS dry and wet separation of coal. Fluidized bed separation was attempted and has promise but much more developmental work on a fluidized bed canister would be required before significant results could be attained. Dry separation of pyrite from coal at this point does not compare with the wet separation because of little control of retention time of the dry powder. If an efficient fluidized bed technique could be devised in the canister then retention time could be increased and high intensity magnetic dry separation of pyrite from coal might indeed be feasible. In addition to pyrite removal about 50 percent of the ash forming constituents in the coal can be separated out by the HIMS process. Freyberger (37) and his associates found that if the ash were floated out of the coal first, 90% of the pyrite could consistently be removed with over 85% yield of coal.

The use of HIMS to concentrate certain metallic ores also merits further investigation. Of the ore minerals tested the following show promise of concentration in the magnetic fraction of the product of HIMS.

Ilmenite
Taconite
Silver
Zinc
Tungsten

A detailed study of many of the industrial minerals and ore minerals should be undertaken using HIMS as a beneficiation process. Further studies of high sulfur coal should be undertaken.

REFERENCES CITED

1. Jones, G. H. British Patents 767,124 and 768,451.

2. Frantz, S. F. U. S. Patent 2,074,085.

3. Oberteuffer, J. A. (1974) Magnetic Separation; A Review of Principles, Devices, and Applications, IEEE Transactions on Magnetics, Vol. Mag-10, No. 2, pp. 223-238.

4. Iannicelli, J., N. Millman, and W. J. D. Stone U.S. Patent 3,471,011.

5. Oder, R. R. and E. R. Price, (1973). Brightness Beneficiation of Kaolin Clays by Magnetic Treatment, TAPPI, Vol. 56, pp. 75-78.

6. Strangway, D. W. (1970). History of the Earth's Magnetic Field, McGraw-Hill New York.

7. Iannicelli, J. (1974). Assessment of High Extraction Magnetic Filtration. Special Report, National Science Foundation.

8. Mills, C. (1977). High Gradient Magnets and The Kaolin Industry. Industrial Minerals, No. 119, pp. 41-45.

9. Iannicelli, J. (1976). High Extraction Magnetic Filtration of Kaolin Clay and Mineral Slimes. Filtration and Separation, Jan. 1976, pp. 15-18.

10. Lefond, S. J. (1975). Industrial Minerals and Rocks, 4th edition, AIME, 1360 p.

11. Thompson, R. D. and H. F. York (1975). The Reserve Base of U.S. Coals by Sulfur Content: Part I. The Eastern States. U. S. Bur. of Mines, Inf. Circ. No. 8680.

12. Thompson, R. D. and H. F. York (1975). The Reserve Base of U.S. Coals by Sulfur Content: Part II. The Western States. U. S. Bur. of Mines, Inf. Circ. No. 8693.

13. Cavallaro, J. A., M. T. Johnston, and A. W. Deverbrouck (1976). Sulfur Reduction Potential of the Coals of the United States, A Revision of R. I. 7633. U. S. Bur. of Mines R.I. 8118.

14. Kester, W. M. Jr. (1965). Magnetic Demineralization of Pulverized Coal. Mining Engineering, Vol. 17.

15. Gluskoter, H. J. and J. A. Simon (1968). Sulfur in Illinois Coals. Illinois State Geol. Surv., Circ. 432, 28 p.

16. Siddiqui, S. (1959). Desulfurization and Concentration of Coal. German.

17. Yurovsky, A. Z. and I. D. Remesnikov (1958). Thermomagnetic Method of Concentrating and Desulfurizing Coal. Coke and Chemistry, Vol. 12, pp. 8-13.

18. Perry, H. (1966). Potential for reduction of Sulfur in Coal by other than Conventional Cleaning Methods. Symposium - Economics of Air Pollution Control, AICHE, 59th Natl. Mtg.

19. Kester, W. M. Jr., (1966). The Effect of High Intensity Magnetic Cleaning on Pulverized High Sulfur, Bituminous Coals. Thesis, Ph.D., School of Mines, West Va. Univ.

20. Wooster, W. A. and N. Wooster (1944). The Magnetic Properties of Coal. Bull. British Coal Utilization Research Assoc., 366 p.

21. Ergun, S. and E. H. Bean (1968). Magnetic Separation of Pyrite from Coals. U. S. Bur of Mines R. I. 7181, 25 p.

22. Kindiq, J. K., and R. L. Turner (1976). Dry Chemical Process to Magnetize Pyrite and Ash for Removal from Coal. AIME Preprint 76-F-366.

23. Wyman, R. A., W. J. D. Stone, and F. H. Hartman (1962). Illustrative Applications of the Jones Wet Magnetic Mineral Separator. Dept. of Mines and Tech. Surveys of Canada, Tech. Bull. 36. 183 p.

24. Murray, H. H. (1976). Clay. Chapter in Paper Coating Pigments, TAPPI Monograph 38, R. W. Hagemeyer, Editor, p. 69-109.

25. Oulton, T. D. (1965). Mining, Production and Uses of Attapulgite Clay Products. SME Preprint 65H39, AIME Annual Meeting, 10 pp.

26. Patterson, S. H. and Murray, H. H. (1975). Clays. Chapter in Industrial Minerals and Rocks, 4th edition, S. J. Lefond, etitor, AIME, pp. 519-585.

27. Shaffer, J. W., (1975). Bauxite Raw Materials. Chapter in Industrial Minerals and Rocks, 4th edition, S. J. Lefond, etitor, p. 443-462.

28. Valeton, I. (1972). Bauxites. Elsevier Pub. Co. Amsterdam, 226 p.

29. Dobrin, M. B. (1960). Introduction to Geophysical Prospecting. McGraw-Hill Book Co., Inc., New York, 269 p.

30. Columbo, A. F., H. D. Jacobs, and D. M. Hopstock (1968). Beneficiation of Western Mesabi Taconite. R.I. 8325, U. S. Bur. of Mines, 13 p.

31. Lawver, J. E., J. L. Wright, and H. R. Kokal (1968). The Behavior of Mesabi Iron and Silicate Minerals in 20-Kilogauss Magnetic Fields. AIME Trans. V. 241, p. 194-203.

32. Hopstock, D. M. (1979). Wet High-Intensity Magnetic Beneficiation of Oxidized Taconites. R.I. 8363, U.S.Bur. of Mines, 24 p.

33. Kelland, D. R. and E. Maxwell (1975). Oxidized Taconite Beneficiation by Continuous High Gradient Magnetic Separation. IEEE Trans. on Magnetics, Vol. Mag-11, No. 5, p. 1582-84.

34. Murray, H. H. (1976). Beneficiation of Selected Industrial Minerals and Coal by High Intensity Magnetic Separation. IEEE Trans. on Magnetics, Vol. Mag-12, p. 498-502.

35. Murray, H. H. (1977). Magnetic Desulfurization of Some Illinois Basin Coals. Amer. Chem. Soc. Symposium Series, No. 64, Coal Desulfurization, T. D. Wheelock, editor, p. 112-120.

36. Murray, H. H. (1978). Beneficiation of Industrial Minerals Using High Intensity Magnetic Separation. Proc. 3rd Int. Ind. Minerals Congress, Paris, France, Metal Bull. Ltd., London.

37. Freyberger, W. L. et. al (1979). Cleaning of Eastern Bituminous Coals by Fine Grinding, Froth Flotation, and High Gradient Magnetic Separation. DOE Contract.

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